Using CERES to Provide Observational Constraints on Cloud Feedbacks and Climate Sensitivity

Kevin M. Grise

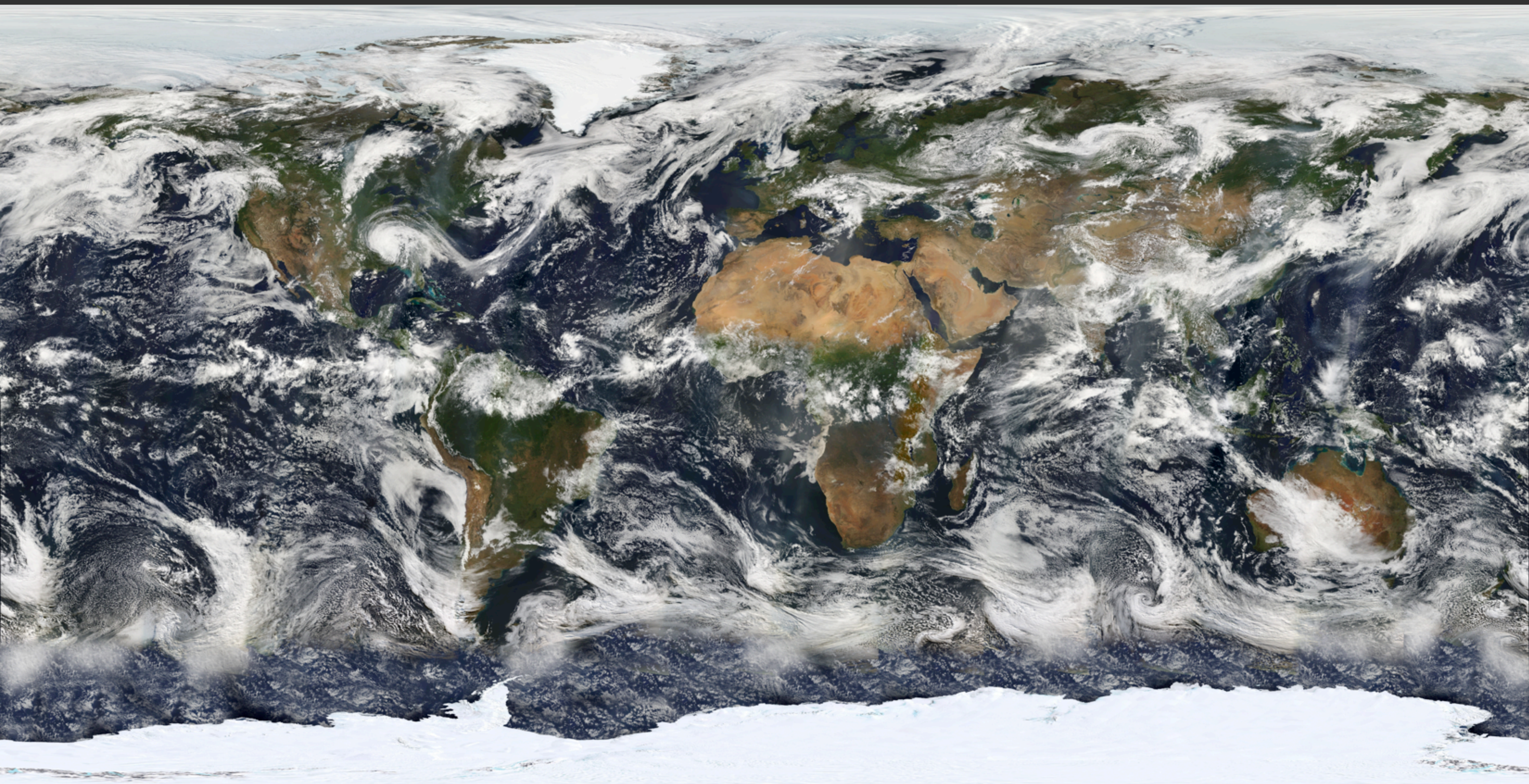
Department of Environmental Sciences

University of Virginia

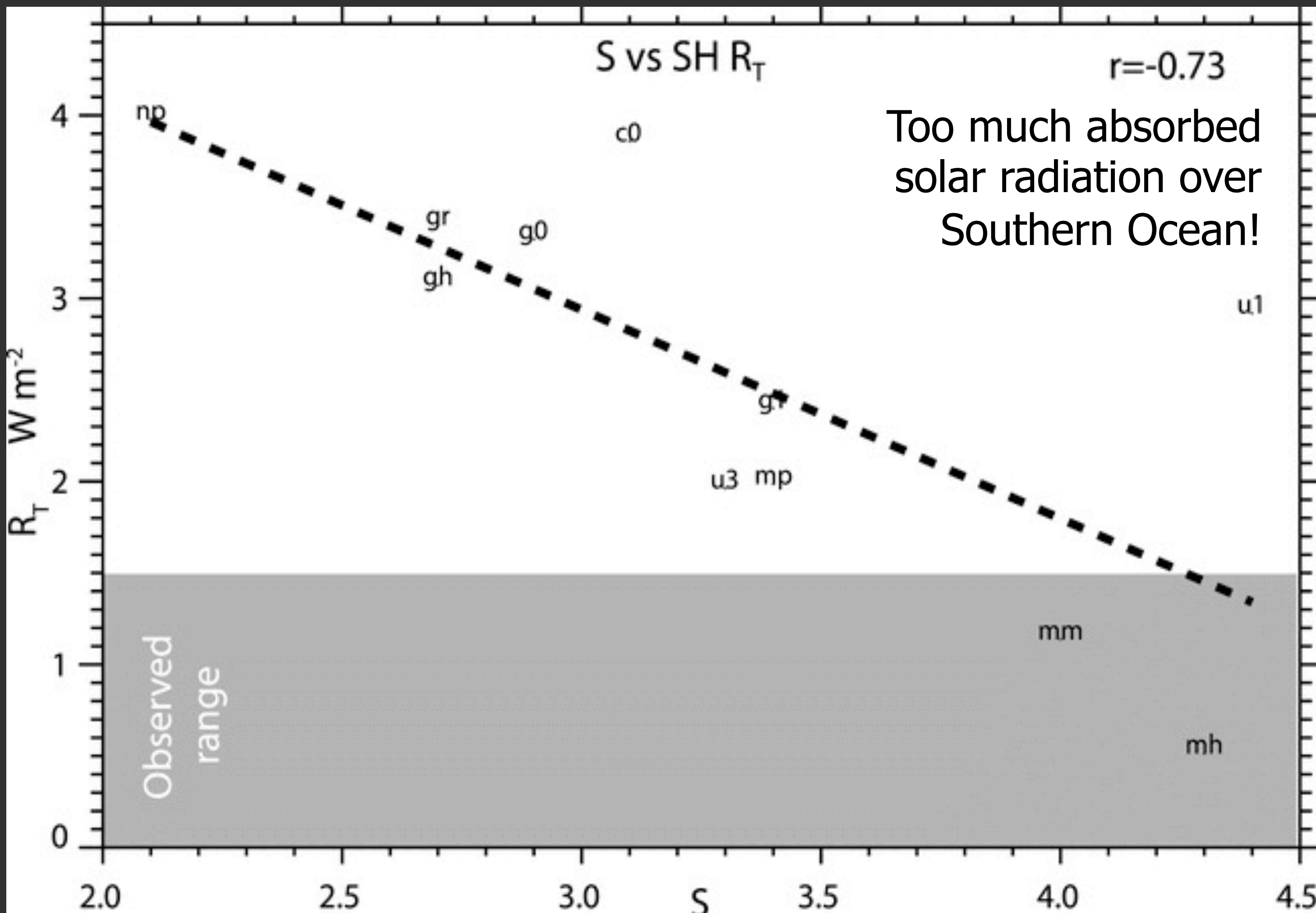
Collaborators: Lorenzo Polvani (LDEO/Columbia), John Fasullo (NCAR), Brian Medeiros (NCAR), George Tselioudis (Columbia/NASA GISS), Yutian Wu (Purdue), Mark Zelinka (LLNL)

UNIVERSITY of VIRGINIA

The Southern Ocean is one of the cloudiest places on Earth!



Climate sensitivity of CMIP3 models is closely linked to the Southern Ocean!



Trenberth and Fasullo (2010)

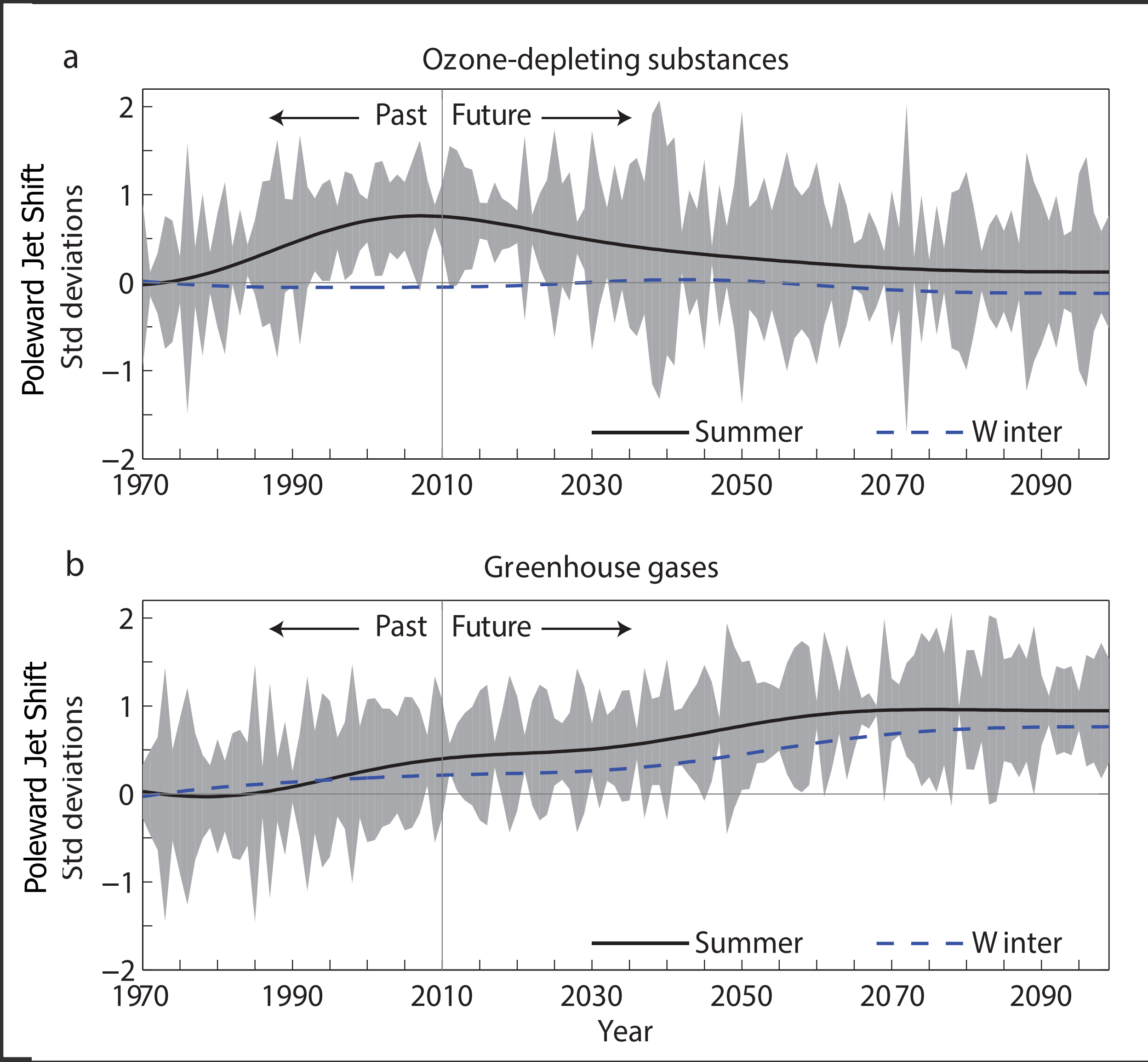
CMIP3 models with most realistic values of present-day Southern Hemisphere net TOA radiation have highest climate sensitivity.

Large changes in dynamics have occurred and will continue to occur over the Southern Ocean.

Over the late 20th century, Southern Hemisphere mid-latitude jet has shifted poleward during summer (DJF) season.

Global climate models indicate that jet shift was due, in large part, to the development of the Antarctic ozone hole.

(Gillett & Thompson 2003,Polvani et al. 2011)

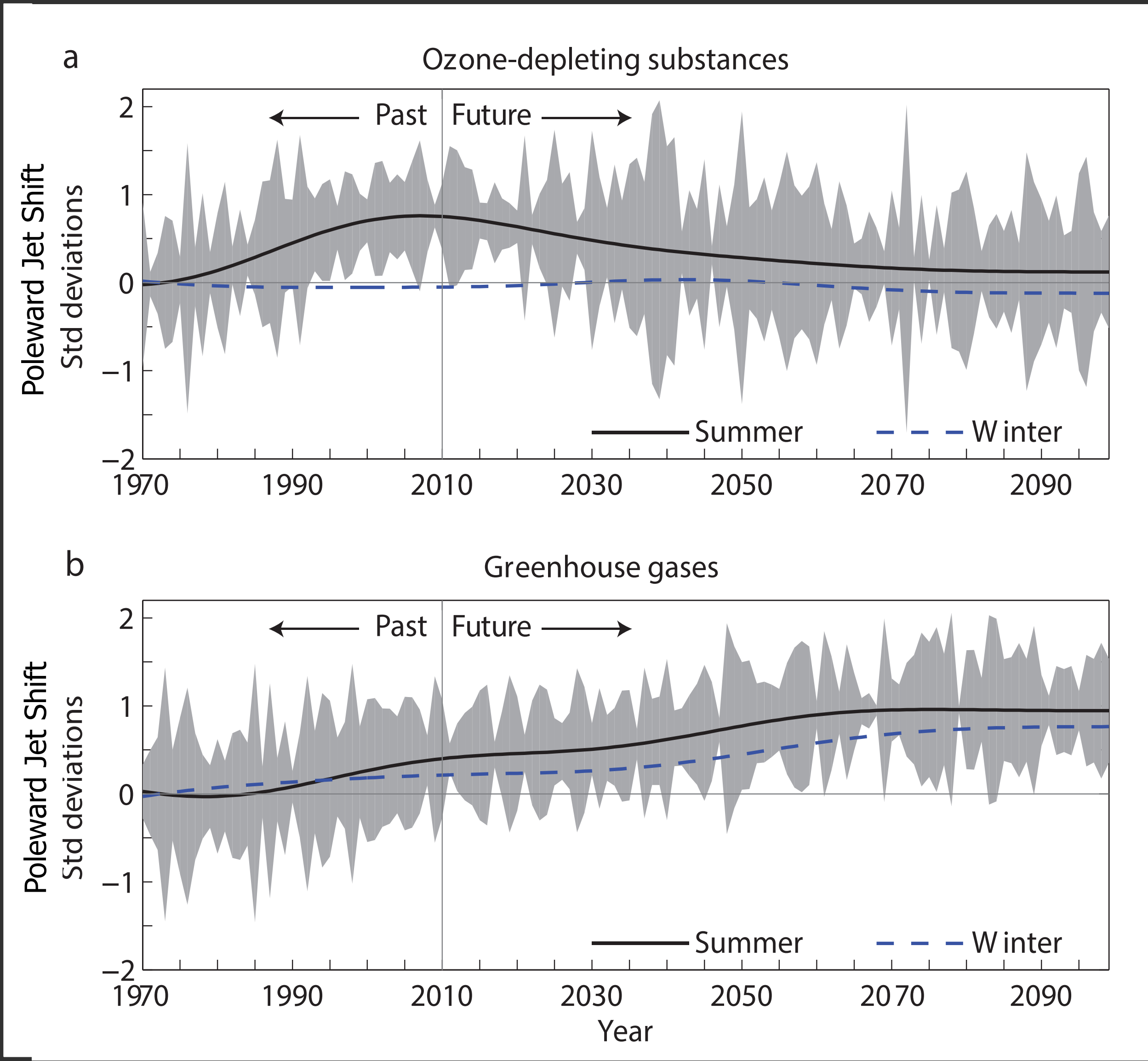


McLandress et al. (2011), Thompson et al. (2011)

Large changes in dynamics have occurred and will continue to occur over the Southern Ocean.

Over the 21st century, it is anticipated that increasing greenhouse gases will act to shift the Southern Hemisphere jet poleward during all seasons.

(e.g., Kushner et al. 2001; Yin 2005; Barnes and Polvani 2013)



McLandress et al. (2011), Thompson et al. (2011)

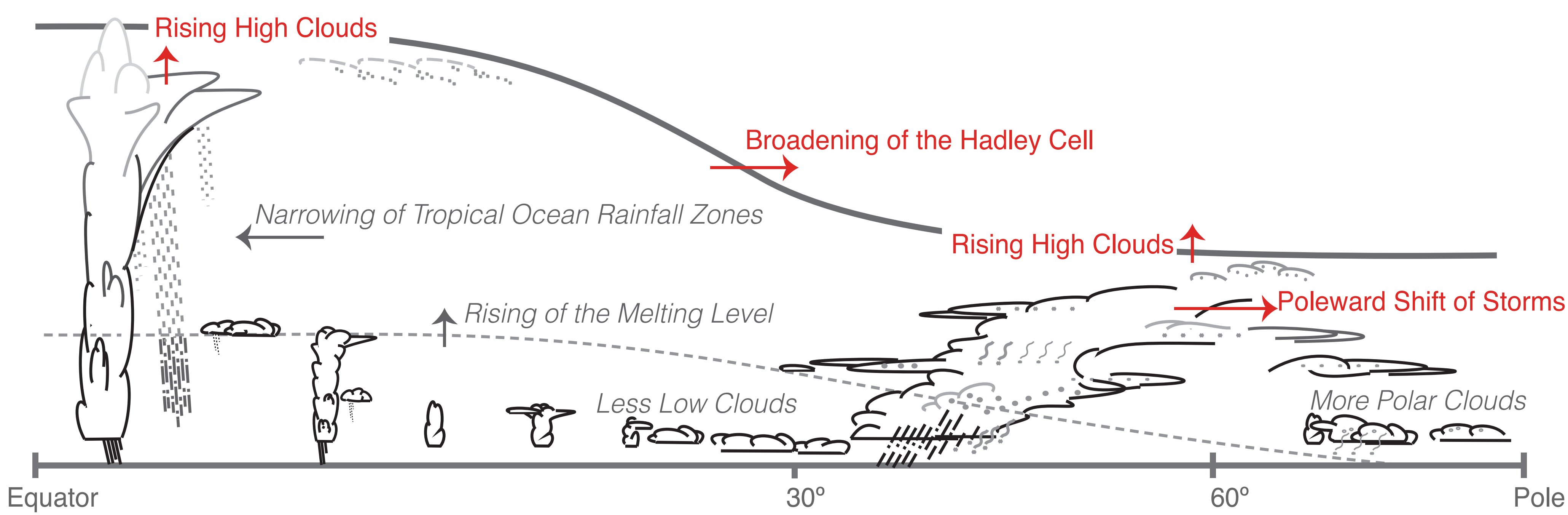
Today's Questions

1) *Has the recent poleward shift in the Southern Hemisphere mid-latitude jet contributed to cloud feedbacks?*

2) *Why are some climate models biased in representing this feedback? And, what are the implications for climate sensitivity?*

Are jet shifts associated with a cloud feedback?

Motivation



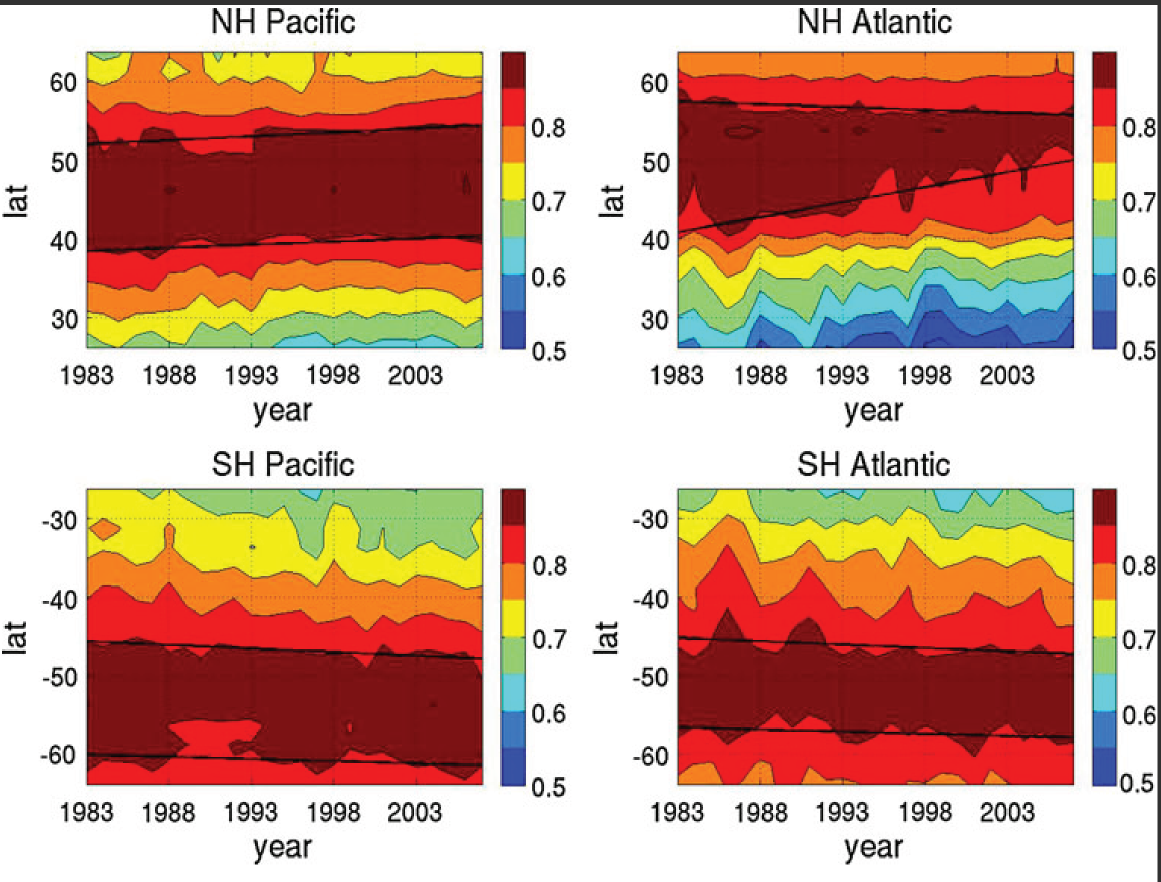
"Observations and most models suggest storm tracks shift poleward in a warmer climate …. which causes further positive feedback via a net shift in cloud cover to latitudes that receive less sunshine."

- Chapter 7, IPCC AR5

Evidence from Observed Trends

Bender et al. (2012)

Annual-mean Total Cloud Fraction



- ISCCP satellite observations suggest poleward shift in mid-latitude cloud patterns.
  - Reduction in total cloud cover
  - Increase in high cloud cover
  - Positive net radiative effect
- Poleward shift in mid-latitude cloud bands also apparent in surface-based cloud observations (Eastman and Warren 2013).

Are jet shifts associated with a cloud feedback?

Method 1: Model Experiments (Grise et al. 2013, GRL)

To test this, we examined the response of Southern Hemisphere clouds and radiation to stratospheric ozone depletion in the NCAR Community Atmosphere Model (CAM3).

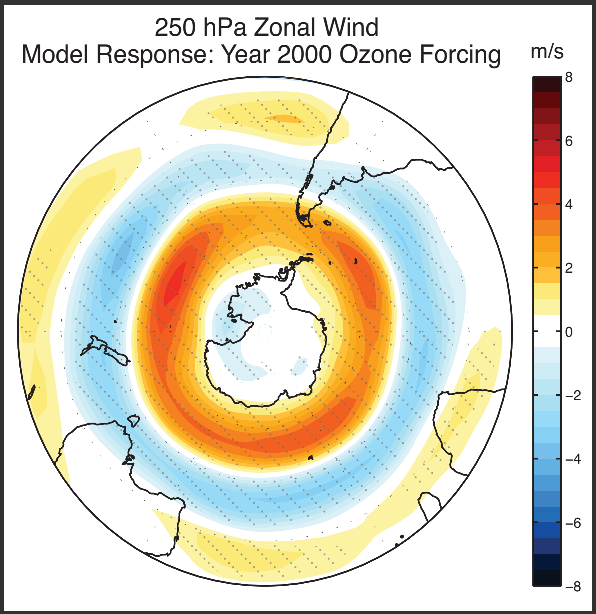
Run	Stratospheric Ozone	Greenhouse Gases
REFERENCE	Observed 1960 levels	Observed 1960 levels
OZONE HOLE	Observed 2000 levels	Observed 1960 levels

- T42 resolution (2.8° x 2.8°), 26 vertical levels
- Coupled to slab ocean and thermodynamic sea ice model
- Single forcing time-slice experiments

Are jet shifts associated with a cloud feedback?

Method 1: Model Experiments (Grise et al. 2013, GRL)

Response to Stratospheric Ozone Depletion

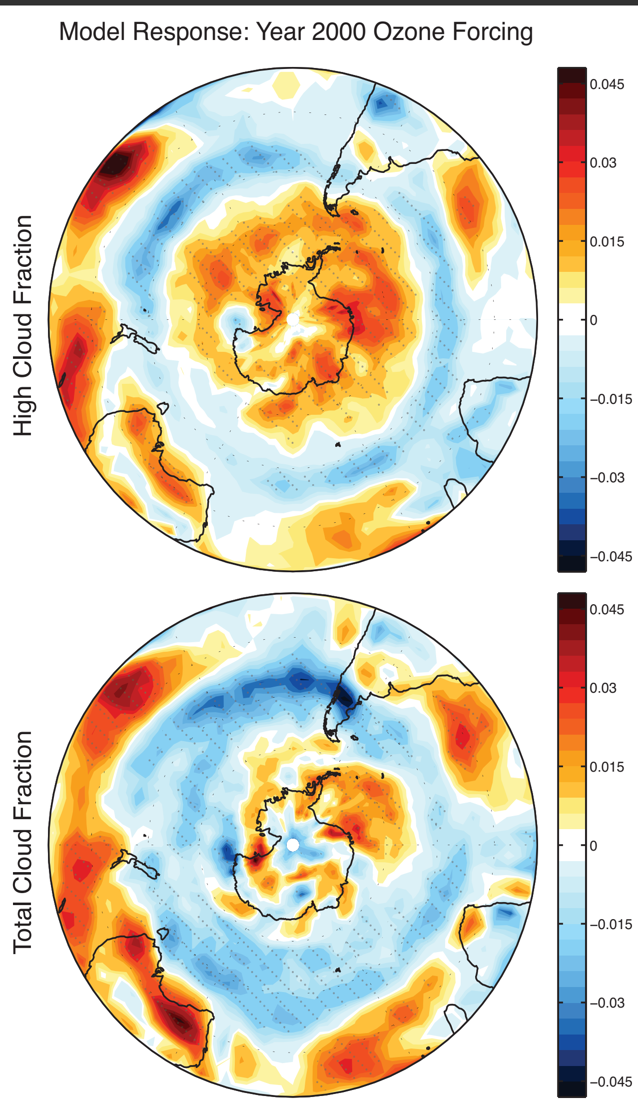


250 hPa Zonal Wind

(December-February)

Are jet shifts associated with a cloud feedback?

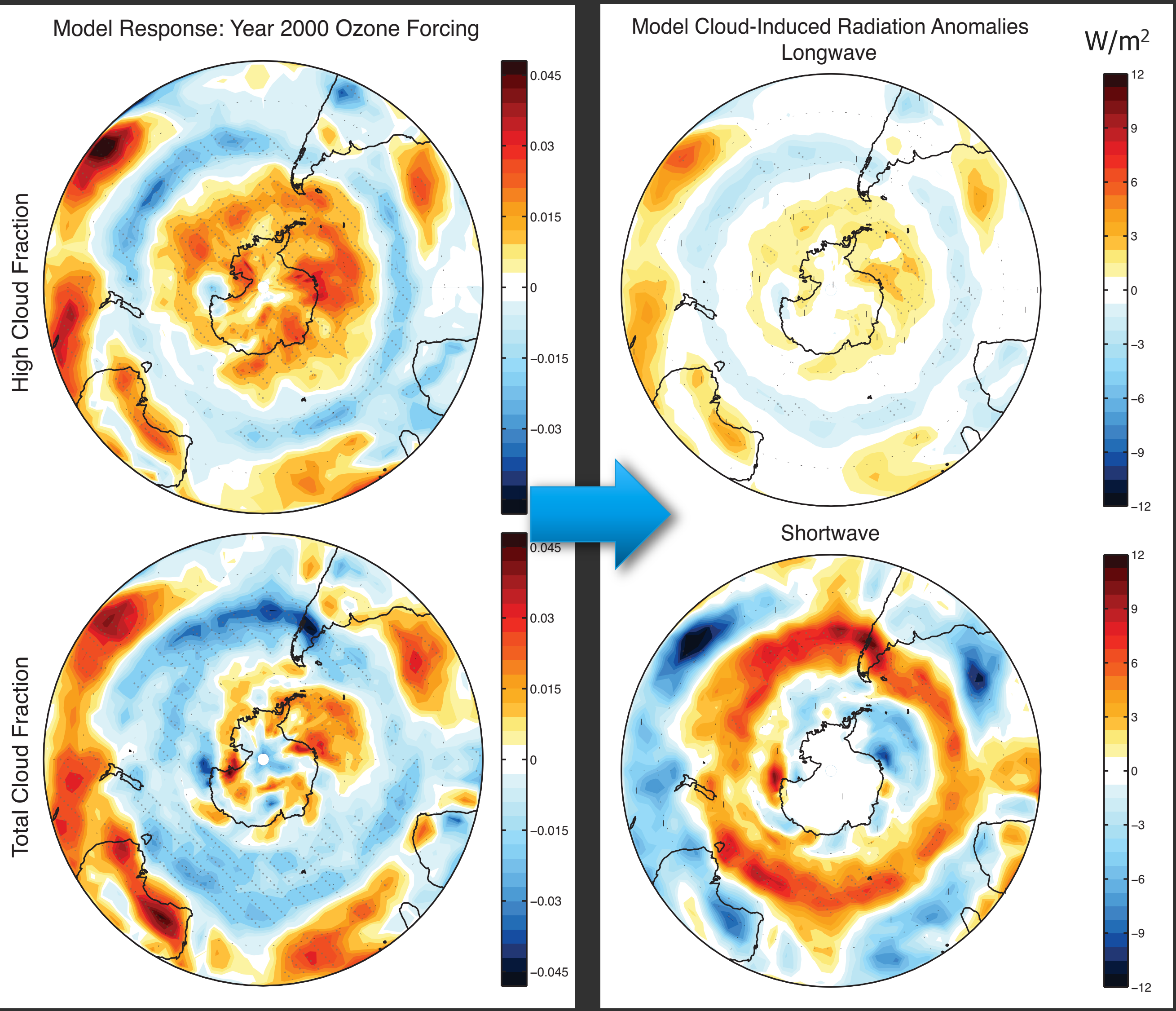
Method 1: Model Experiments (Grise et al. 2013, GRL)



- When the SH summertime jet moves poleward:
  - High and mid-level clouds move poleward with the jet.
  - Total cloud fraction is reduced at SH mid-latitudes.

Are jet shifts associated with a cloud feedback?

Method 1: Model Experiments (Grise et al. 2013, GRL)



$$K \equiv \frac{\partial R}{\partial C}.$$

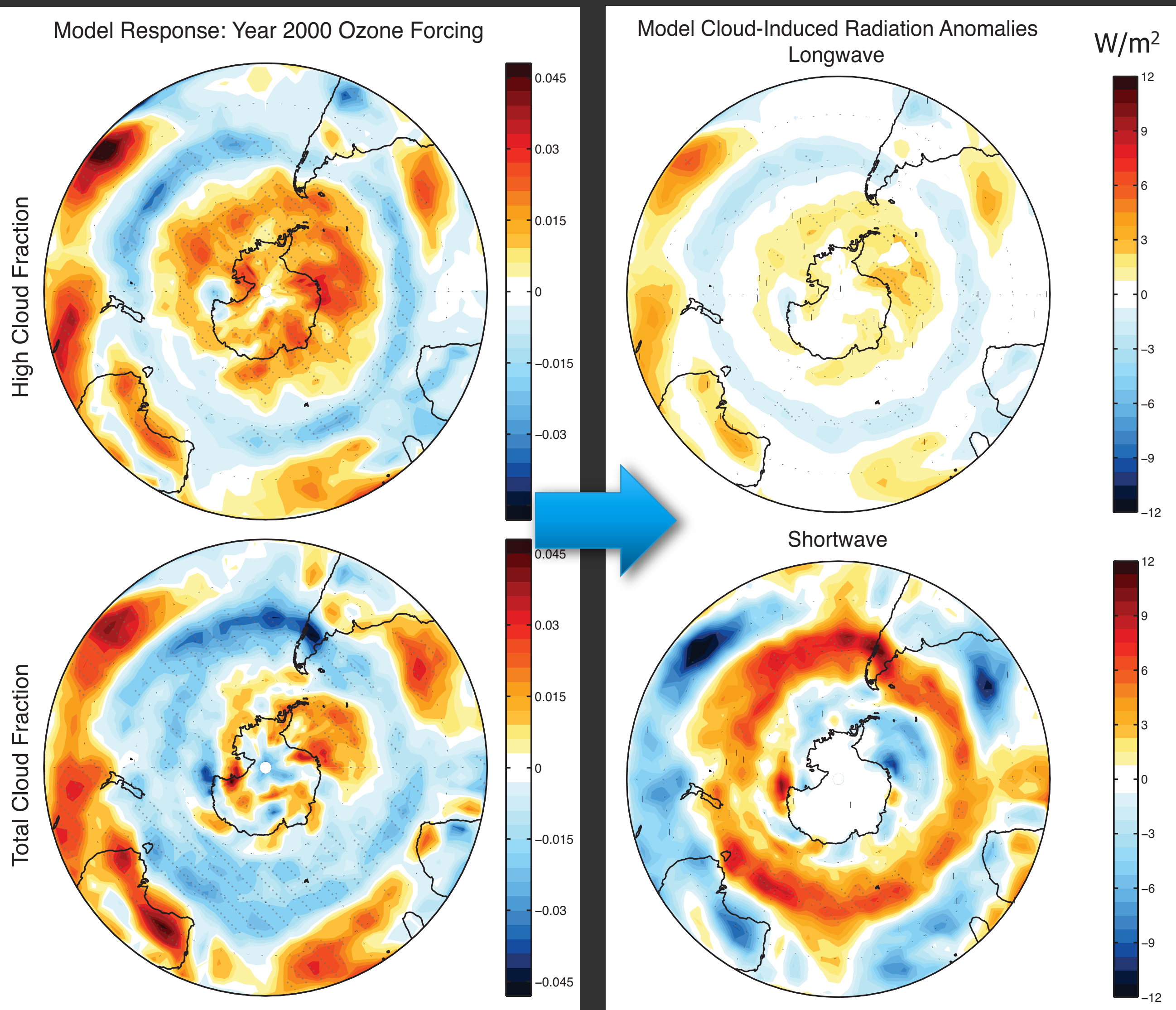
$$\Delta R = K \Delta C.$$

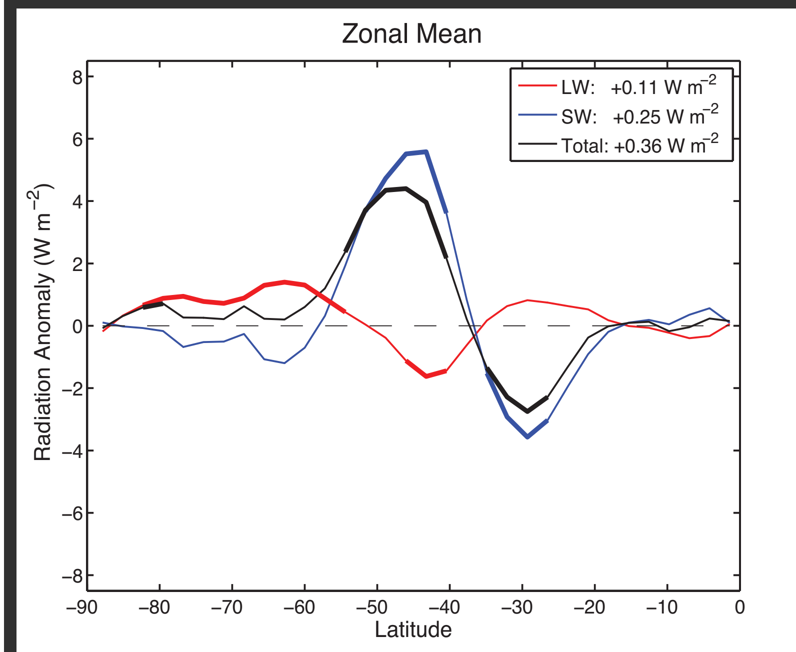
Cloud Radiative Kernel

(Zelinka et al. 2012)

Are jet shifts associated with a cloud feedback?

Method 1: Model Experiments (Grise et al. 2013, GRL)





Cloud Radiative Kernel

(Zelinka et al. 2012)

Are jet shifts associated with a cloud feedback?

Method 1: Model Experiments (Grise et al. 2013, GRL)

Summary of Findings:

- Antarctic stratospheric ozone depletion is linked to poleward shift in Southern Hemisphere mid-latitude tropospheric jet during summer.
- Ozone-hole-induced jet shift is associated with poleward shift in high clouds and reduction in low clouds across Southern Ocean.
- The ozone hole **may** have a positive net "indirect effect" on Earth's radiation budget through shifts and changes in cloud patterns.

Are jet shifts associated with a cloud feedback?

Method 2: Interannual Variability (Grise & Polvani 2014, J. Climate)

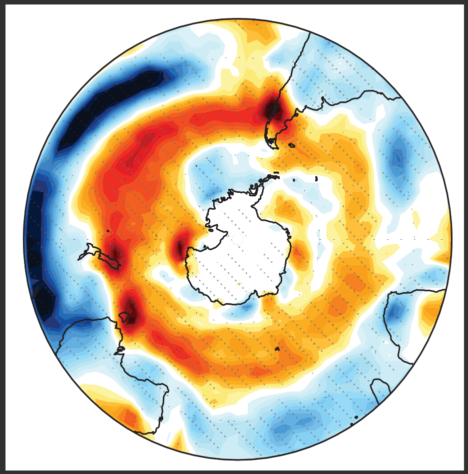
Methodology: We evaluate the cloud-radiative effect anomalies associated with a 1° poleward jet shift. To do this, we:

- Look at interannual variability in CMIP5 pre-industrial control runs and historical satellite record.
- Focus on December-February season.
- Define Southern Hemisphere jet latitude time series using 850-hPa zonal-mean zonal wind maximum.
- Regress cloud-radiative effect anomalies (from seasonally varying climatology) onto jet latitude time series.

Are jet shifts associated with a cloud feedback?

Method 2: Interannual Variability (Grise & Polvani 2014, J. Climate)

Shortwave Cloud-Radiative Effect Anomalies Associated with 1° Poleward Jet Shift



CAM3

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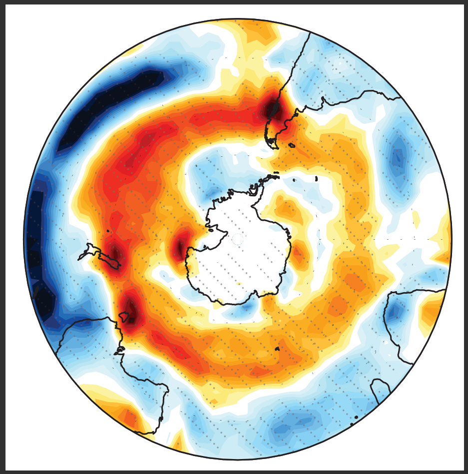
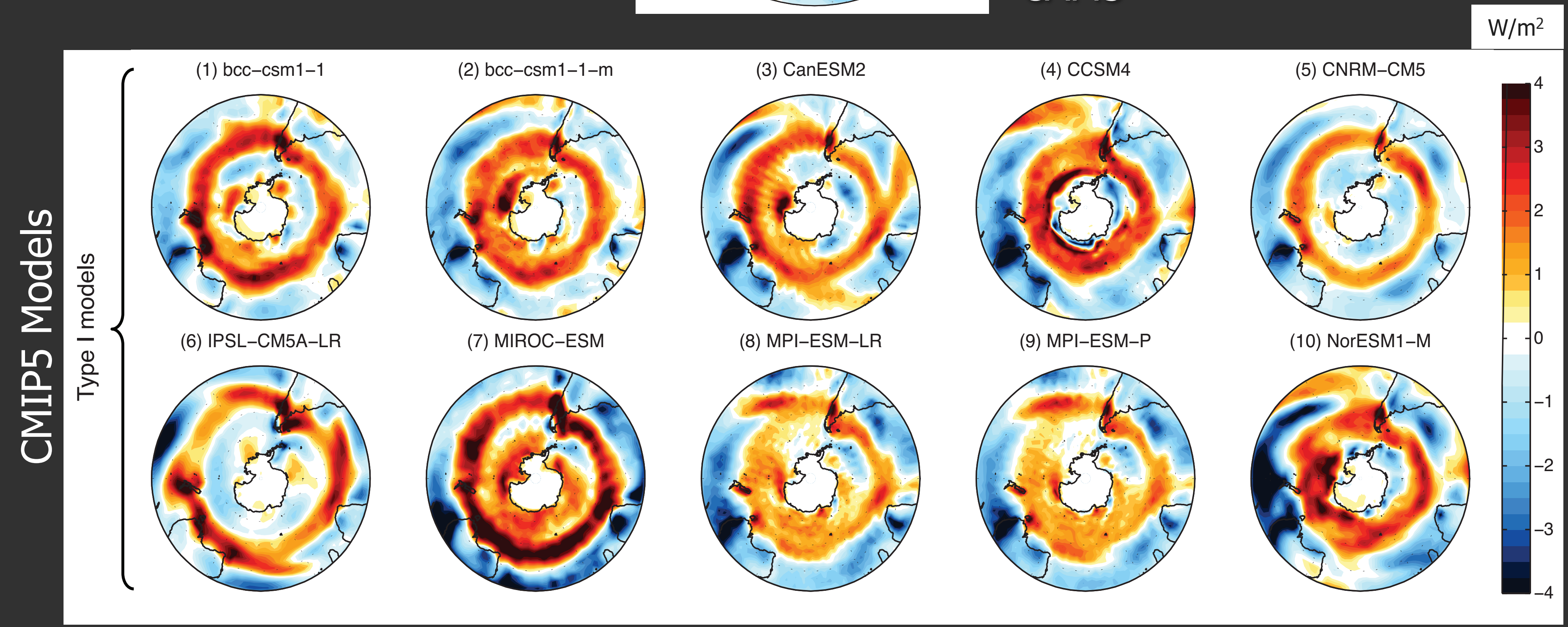
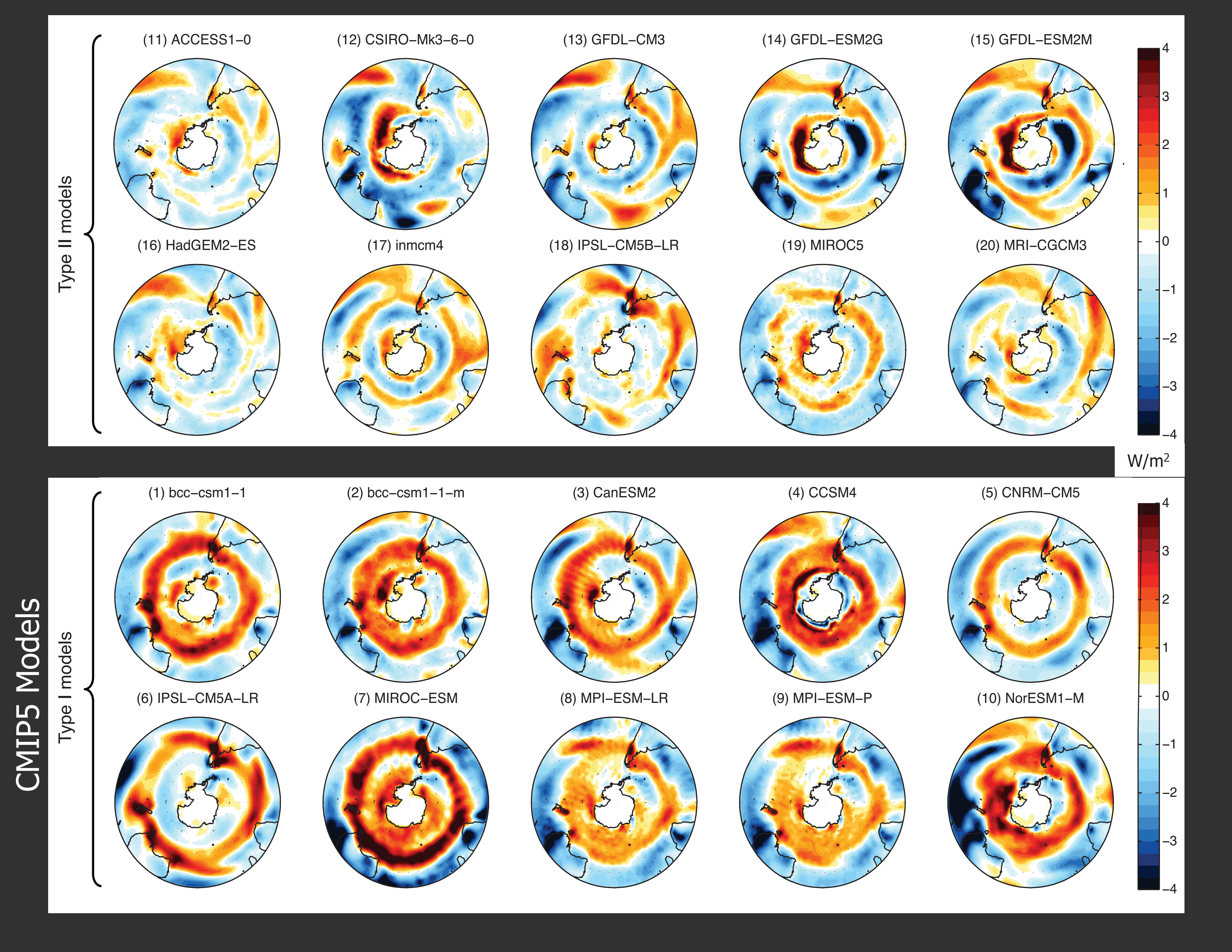


CAM3



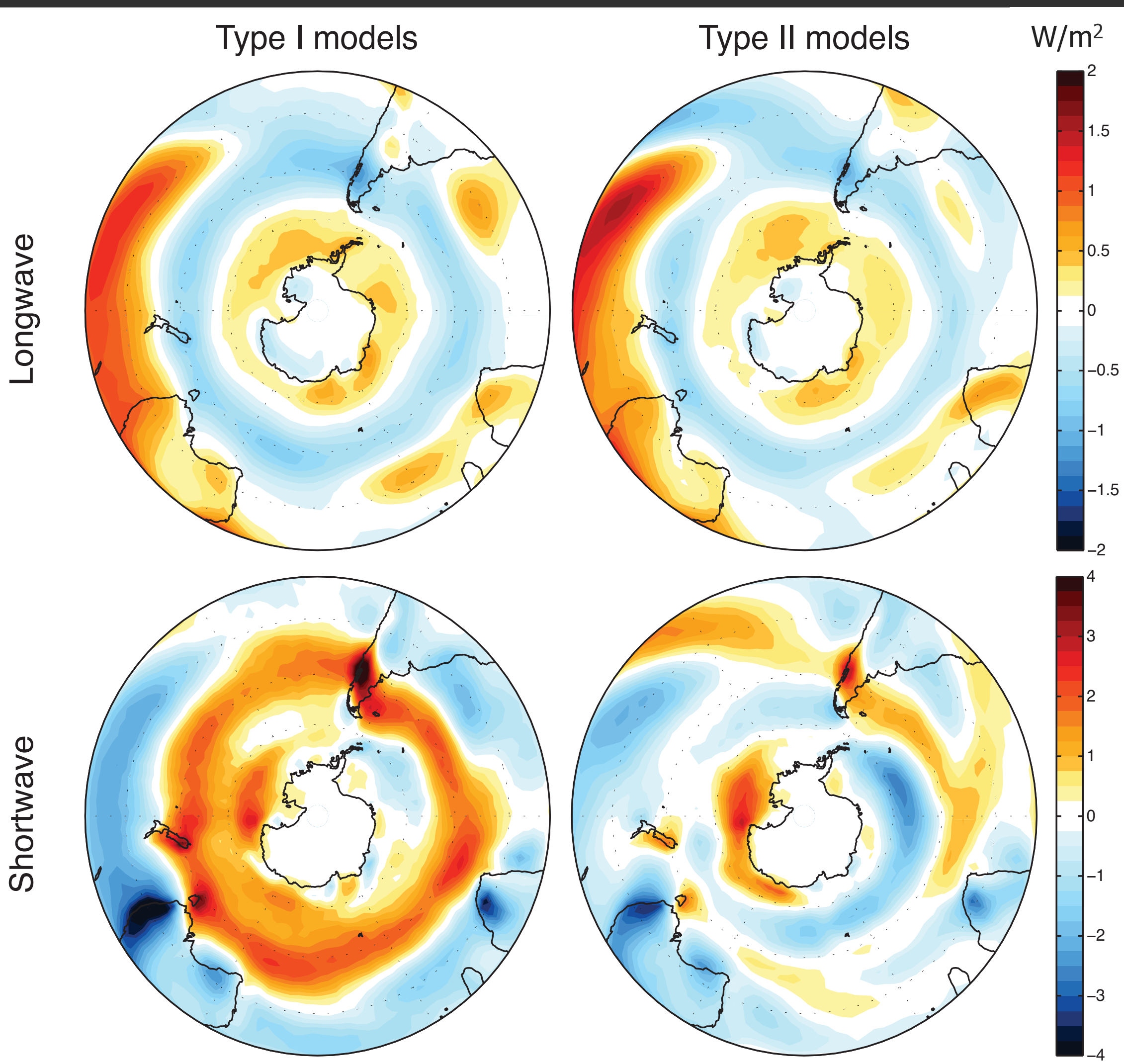


(11) ACCESS1−0
(12) CSIRO−Mk3−6−0
(13) GFDL−CM3
(14) GFDL−ESM2G
(15) GFDL−ESM2M
(16) HadGEM2−ES
(17) inmcm4
(18) IPSL−CM5B−LR
(19) MIROC5
(20) MRI−CGCM3
Type II models
(1) bcc−csm1−1
(2) bcc−csm1−1−m
(3) CanESM2
(4) CCSM4
(5) CNRM−CM5
(6) IPSL−CM5A−LR
(7) MIROC−ESM
(8) MPI−ESM−LR
(9) MPI−ESM−P
(10) NorESM1−M
Type I models
CMIP5 Models
4
3
2
1
0
−1
−2
−3
−4
W/m^2

Are jet shifts associated with a cloud feedback?

Method 2: Interannual Variability (Grise & Polvani 2014, J. Climate)

CMIP5 Models

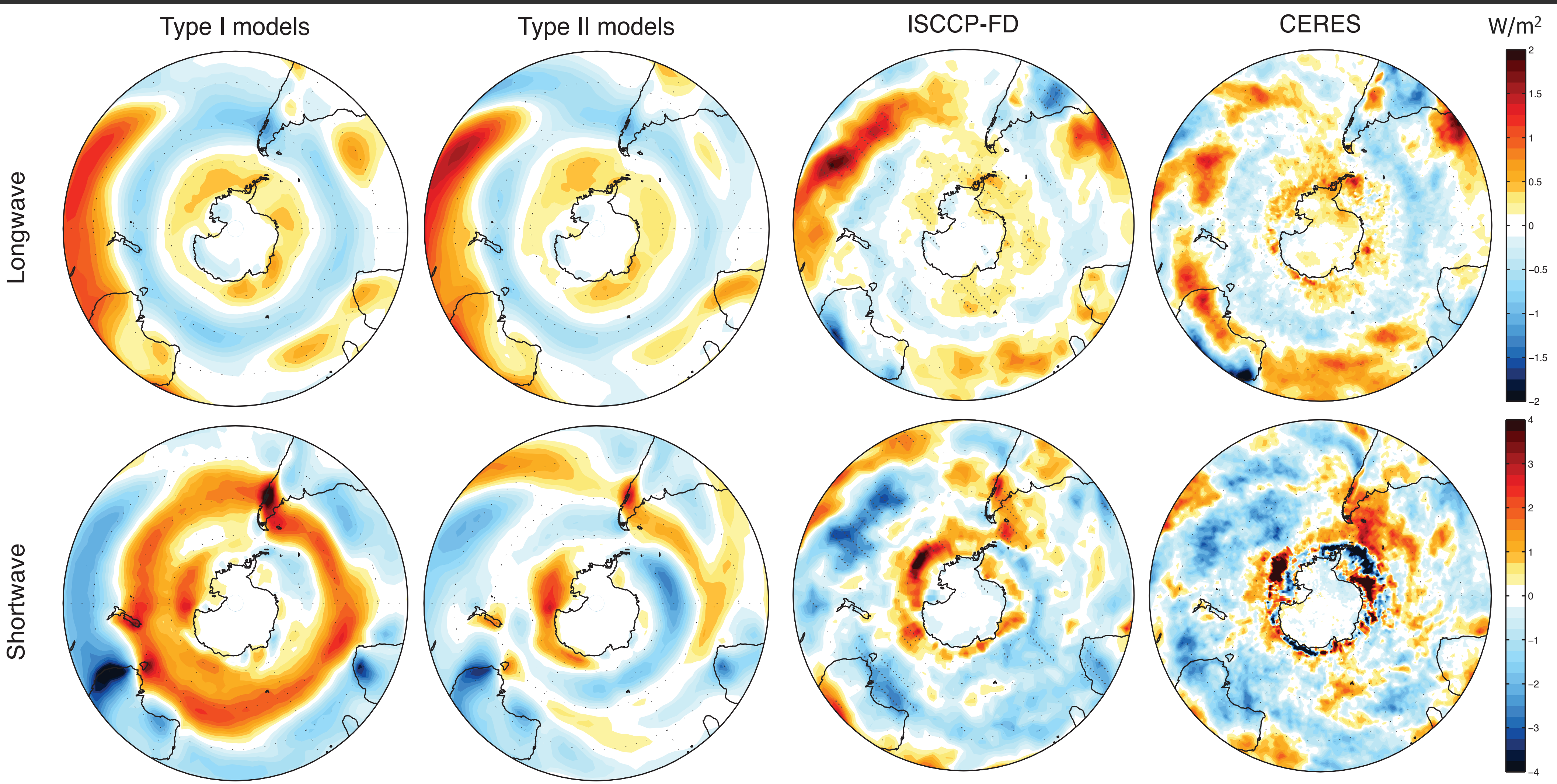


Cloud-Radiative Effect Anomalies
Associated with 1° Poleward Jet Shift

Are jet shifts associated with a cloud feedback?

Method 2: Interannual Variability (Grise & Polvani 2014, J. Climate)

CMIP5 Models | Satellite Observations



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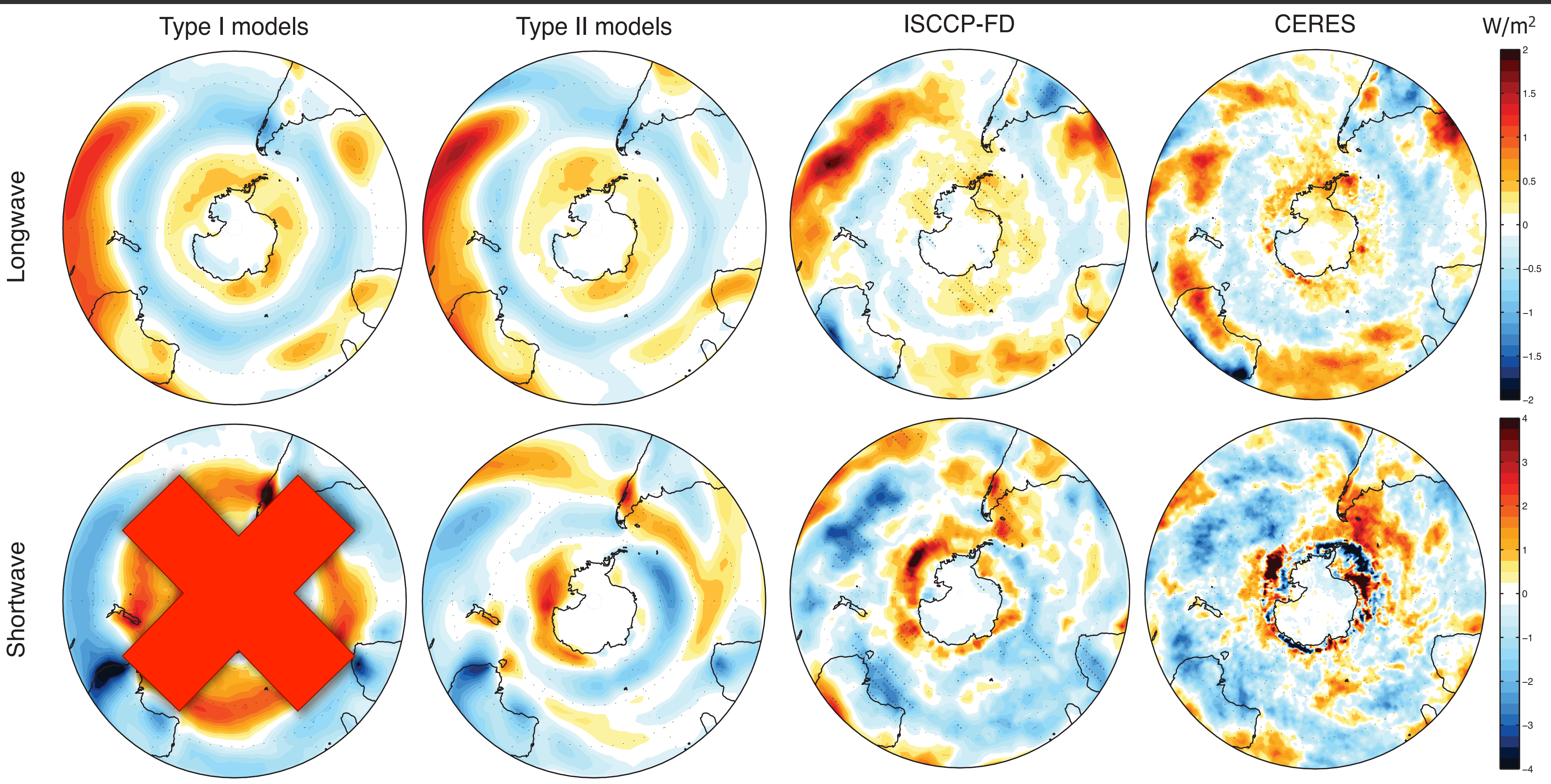


Cloud-Radiative Effect Anomalies
Associated with 1° Poleward Jet Shift

Are jet shifts associated with a cloud feedback?

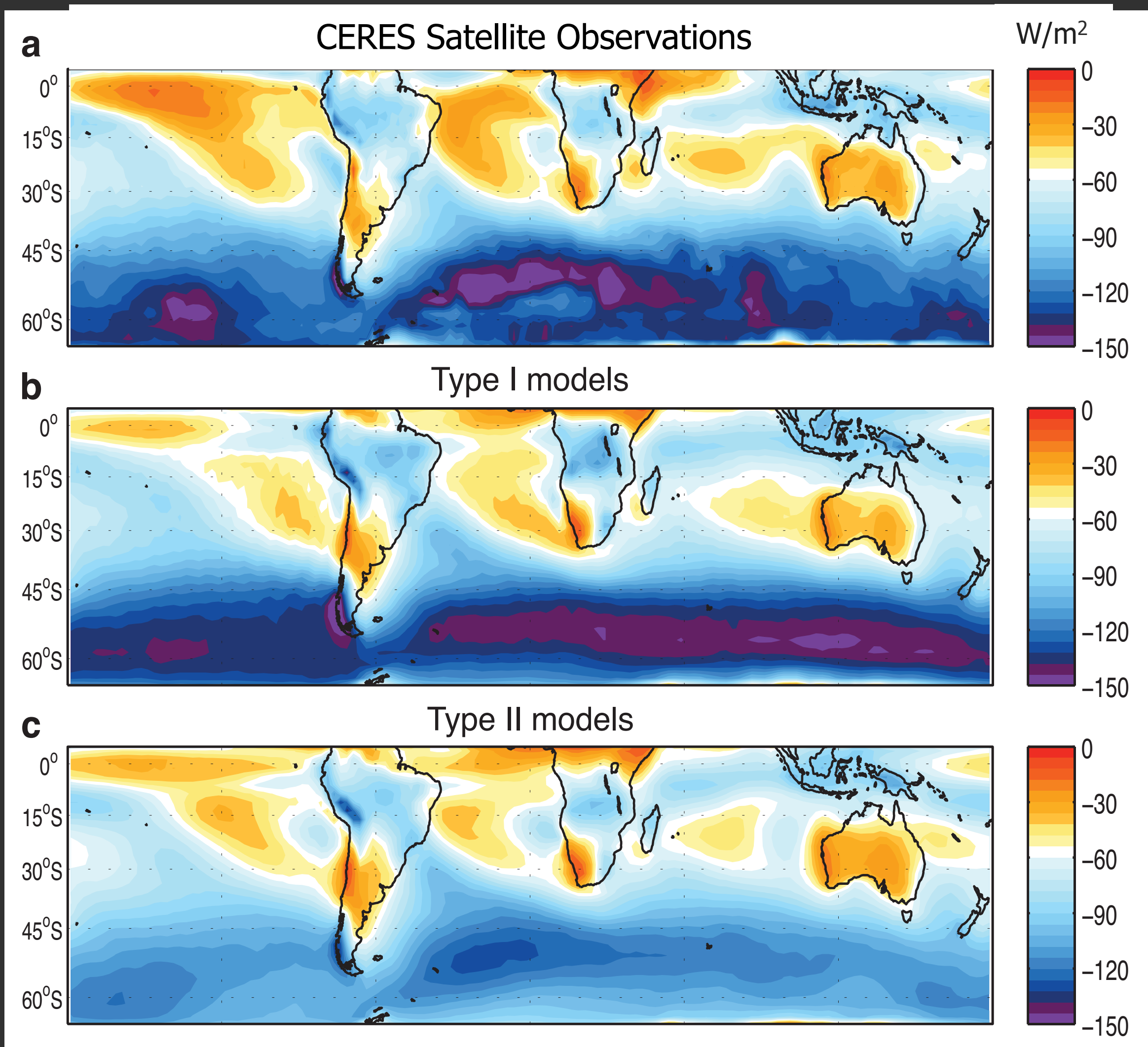
Method 2: Interannual Variability (Grise & Polvani 2014, J. Climate)

Summary of Findings:

- Cloud-induced radiation anomalies associated with a Southern Hemisphere jet shift are highly variable among climate models:
    - Type I models: Strong coupling between SH mid-latitude jet and reflection of solar radiation by clouds (as in CAM3)
    - Type II models: Little net shortwave cloud-radiative effect associated with a jet shift
- The behavior of the type II models is more realistic when compared to satellite observations.

Why are climate models biased in representing this effect?

Are the models biased in the climatology?



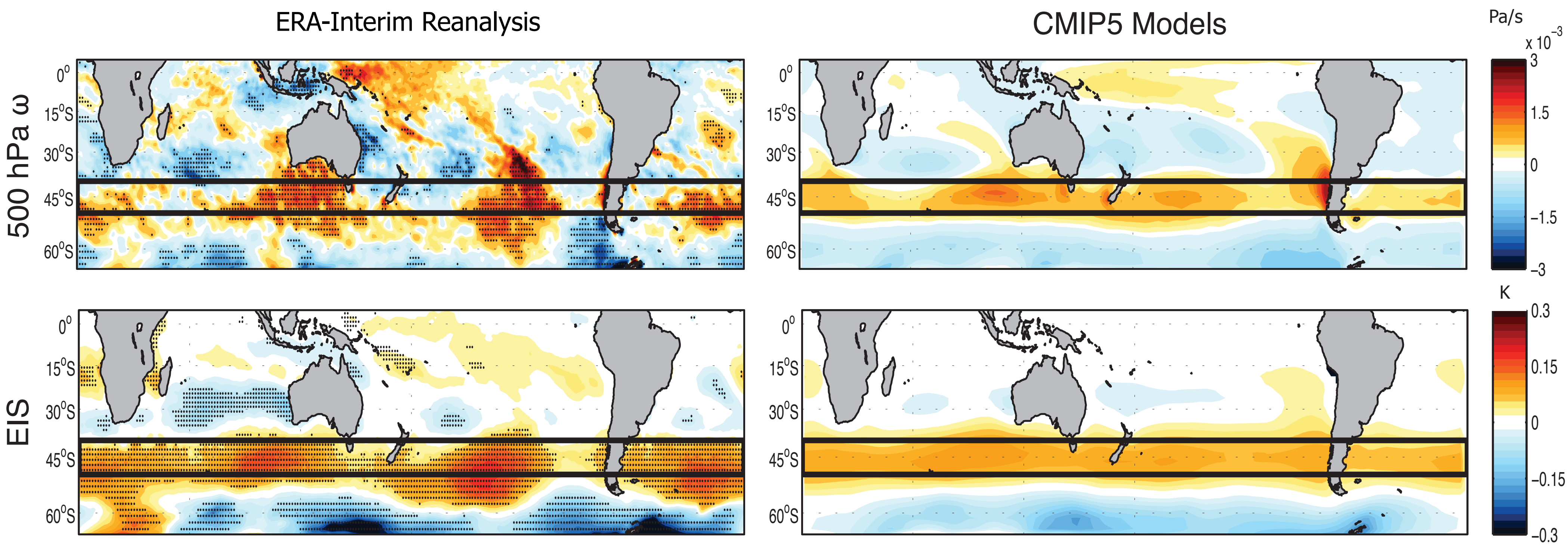
Shortwave
Cloud-Radiative Effect
Climatology
(December-February)

(Grise and Polvani 2014)

- Type I models: Bright, zonally symmetric Southern Ocean clouds
- Type II models: Less bright, more zonally asymmetric clouds

Understanding the model biases

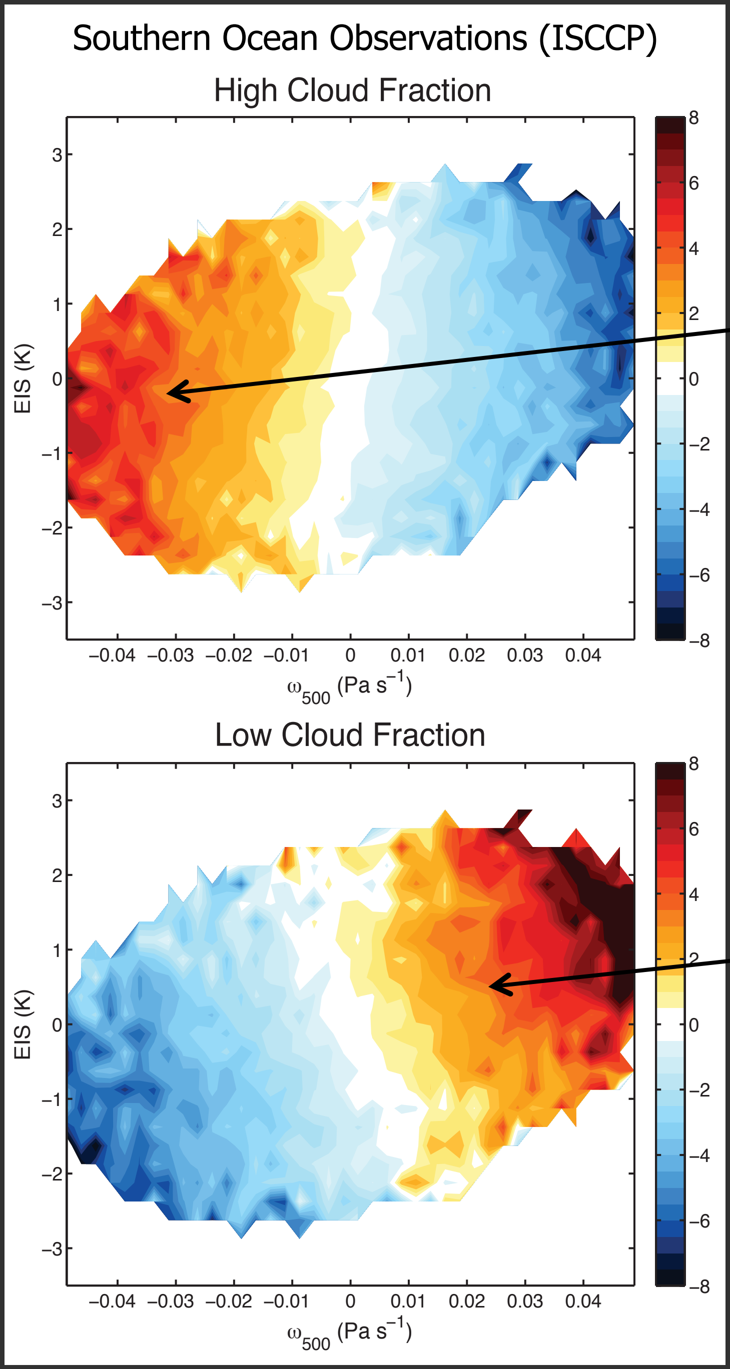
Anomalies Associated with 1° Poleward Jet Shift



Grise and Medeiros (submitted)

When the jet shifts poleward, downward vertical velocity and increased lower tropospheric stability (EIS) anomalies occur equatorward of the jet.

Understanding the model biases

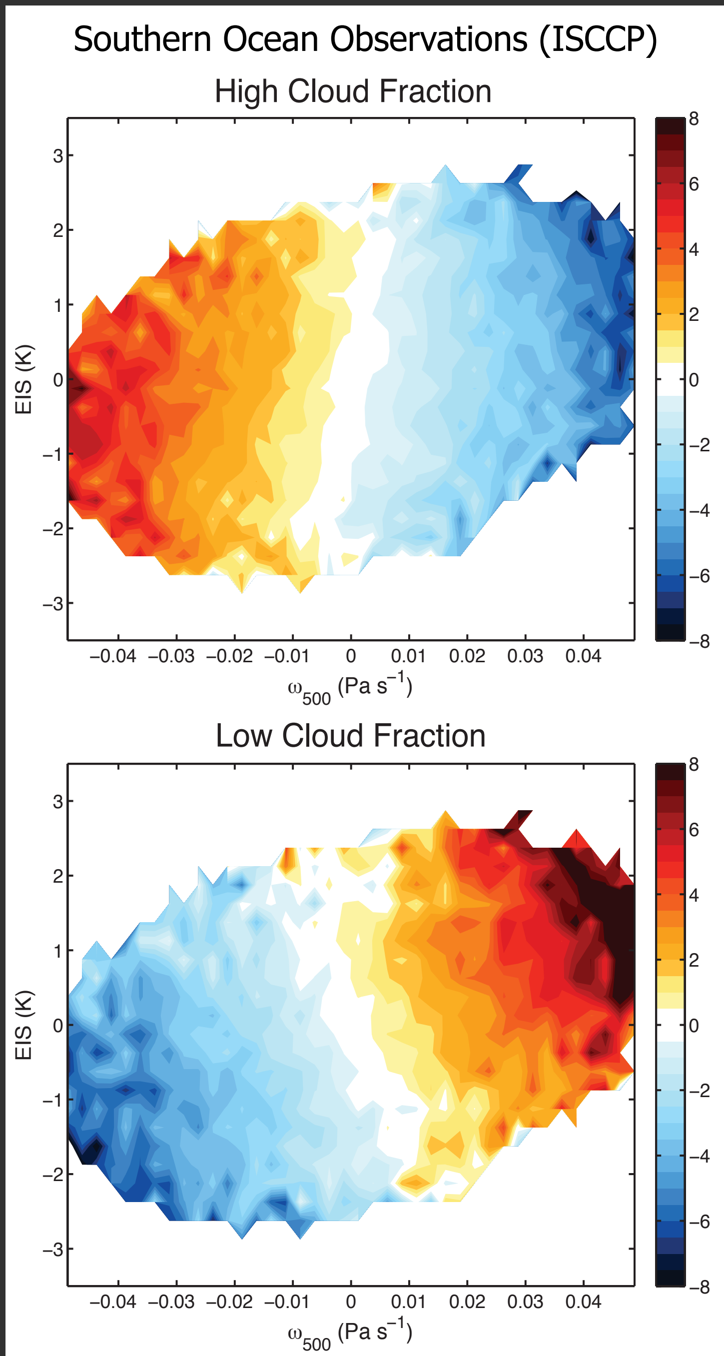


Grise and Medeiros (submitted)

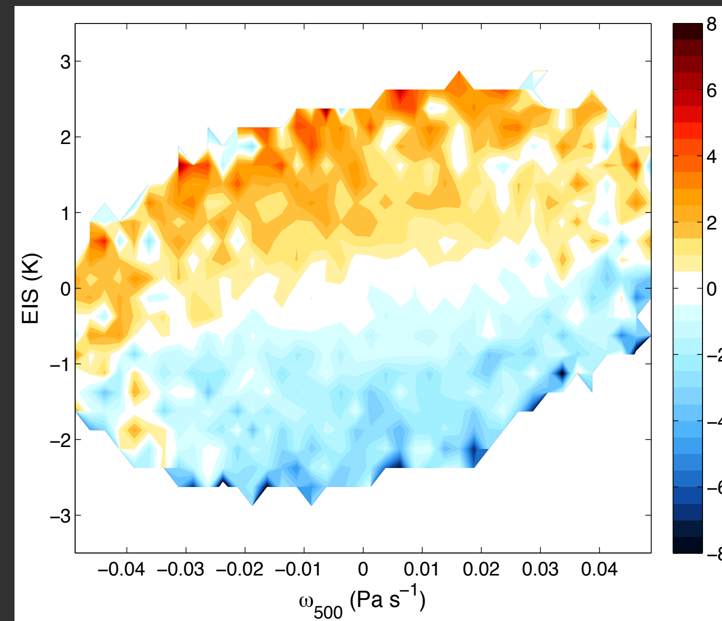
High clouds increase with upward vertical velocity anomalies.

Low clouds increase with downward vertical velocity anomalies.

Understanding the model biases



Total Cloud Fraction

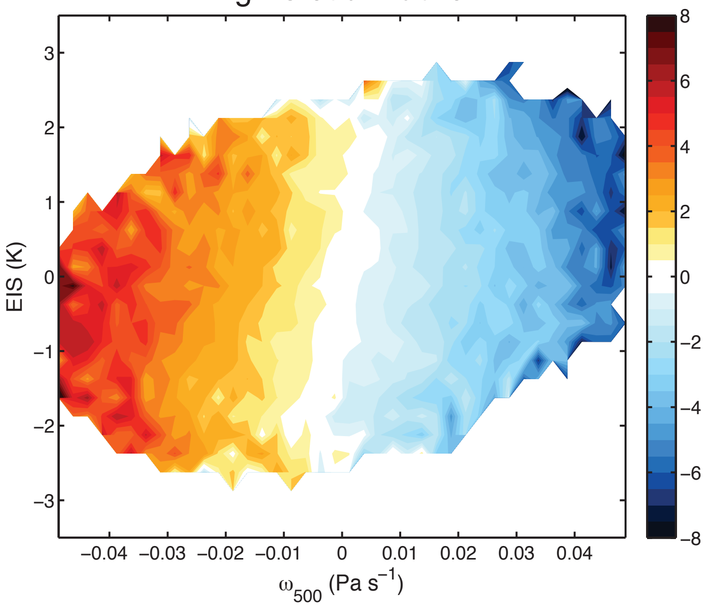


Grise and Medeiros (submitted)

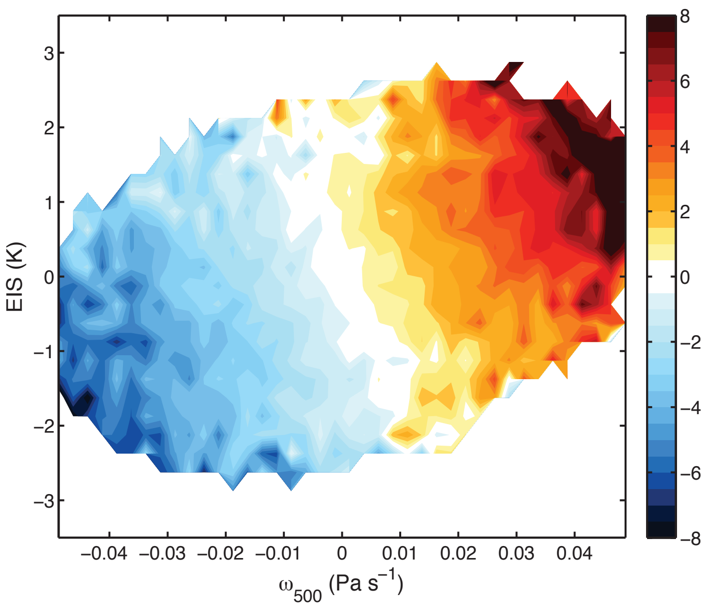
Understanding the model biases

Southern Ocean Observations (ISCCP)

High Cloud Fraction



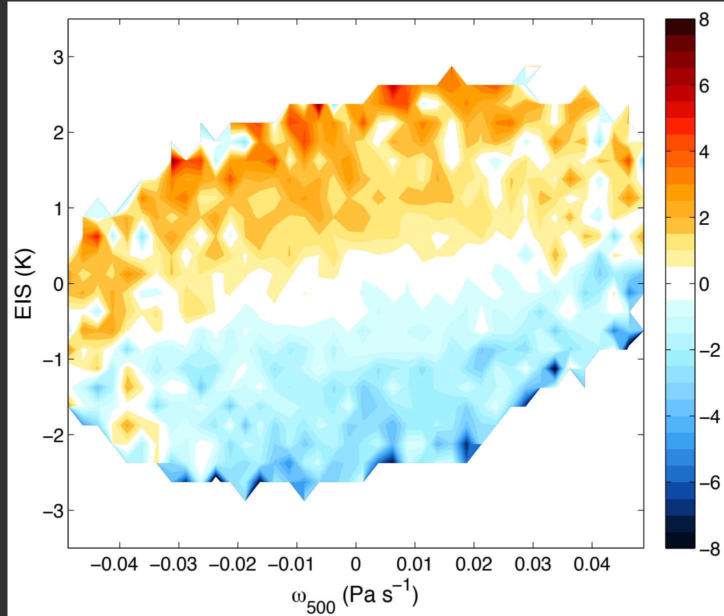
Low Cloud Fraction



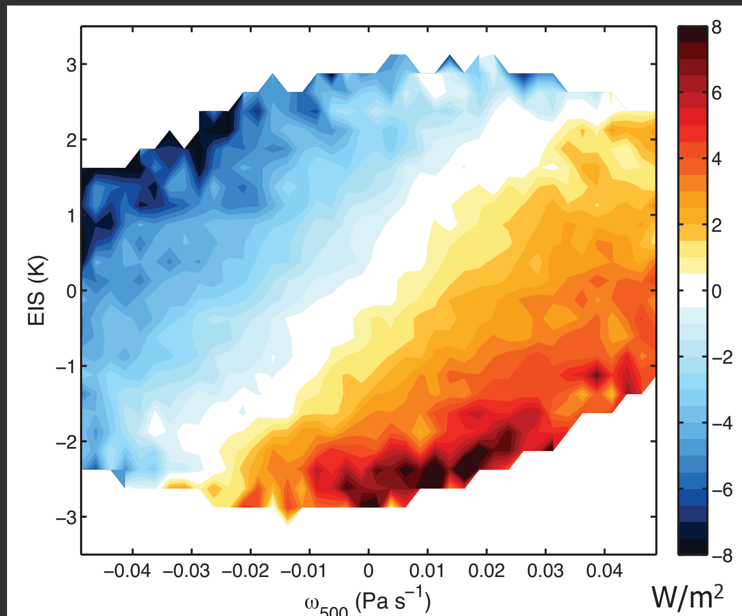
Grise and Medeiros (submitted)

+

Total Cloud Fraction

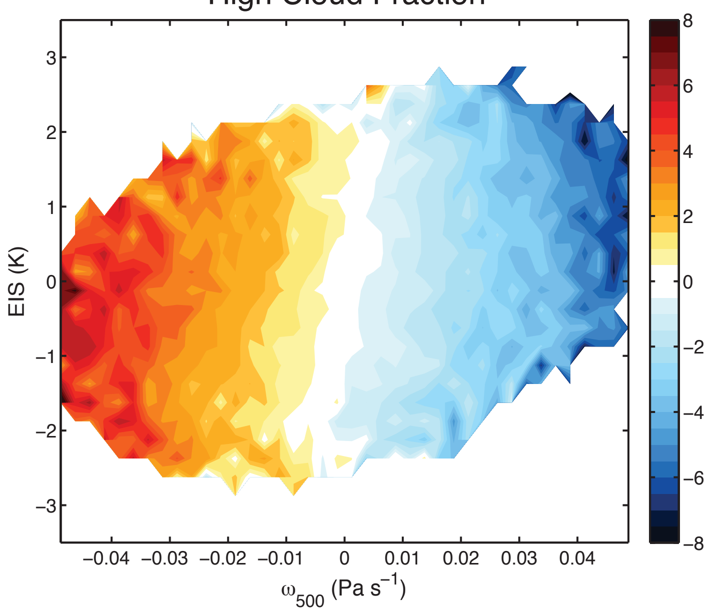


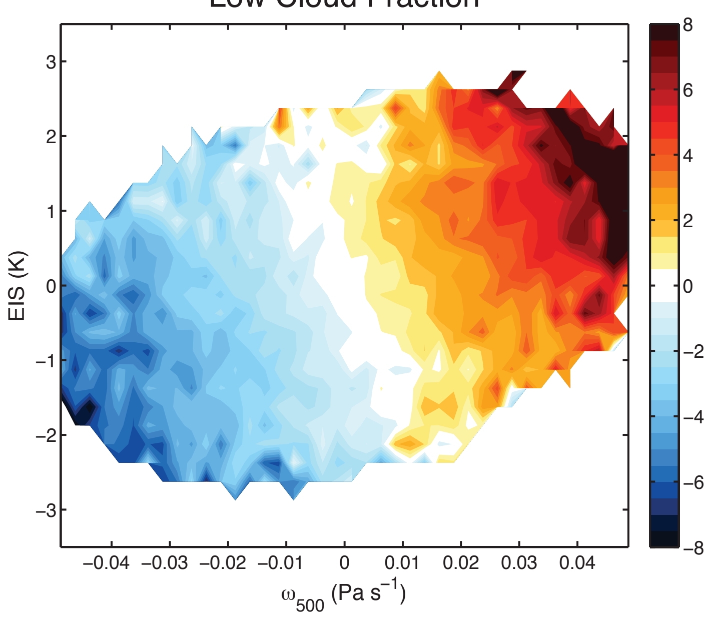
Shortwave Cloud-Radiative Effect (CERES)



Understanding the model biases

Southern Ocean Observations (ISCCP)





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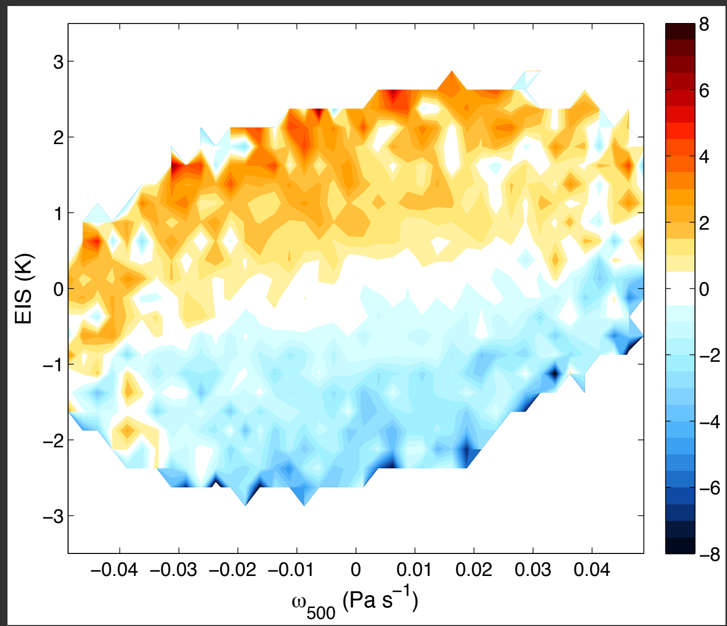
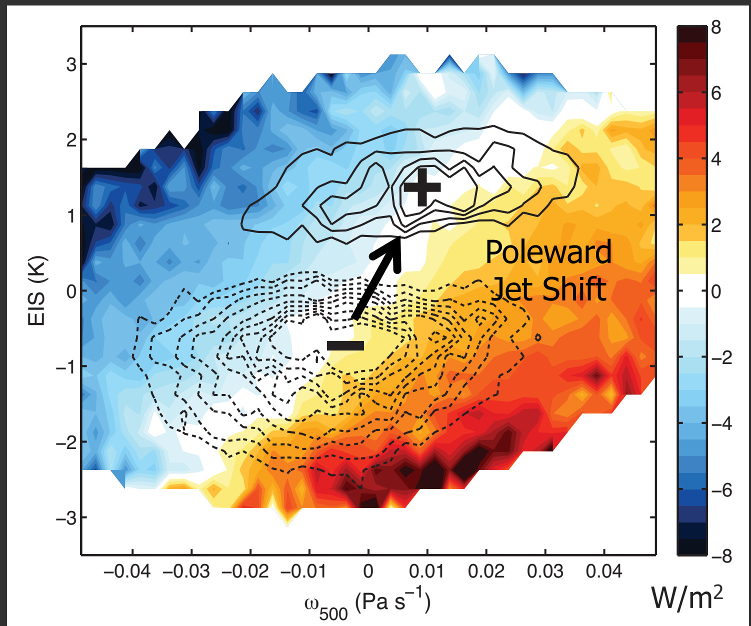
Total Cloud Fraction

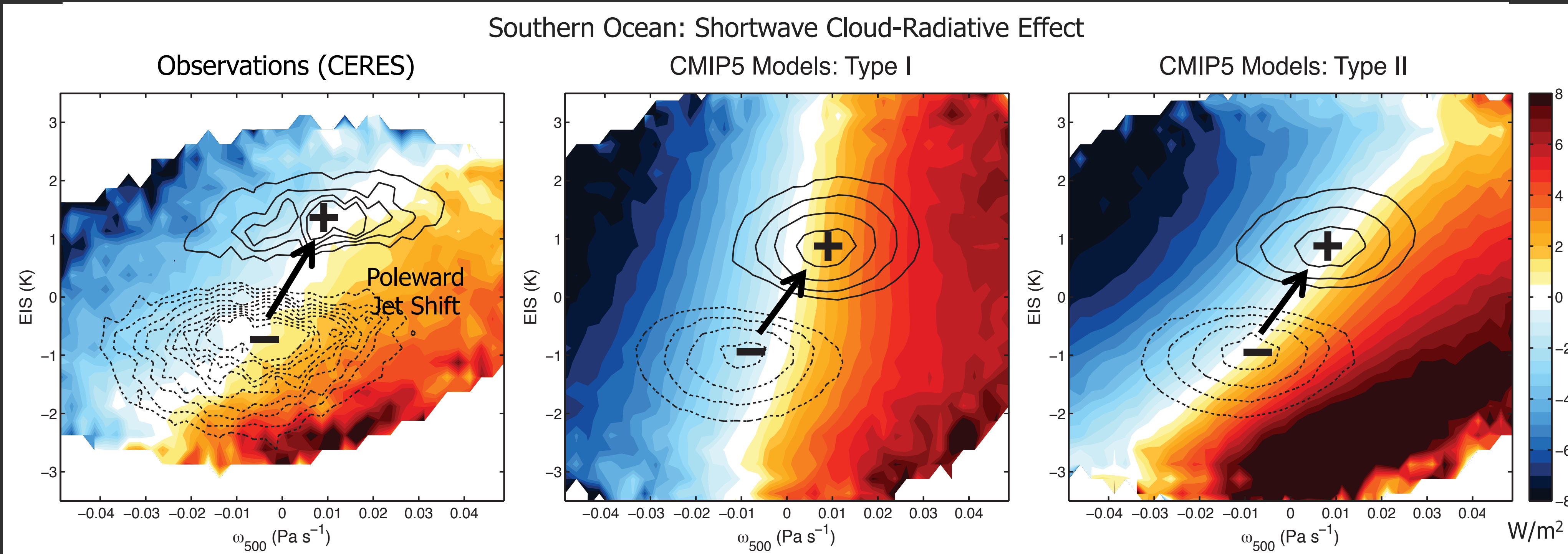


Shortwave Cloud-Radiative Effect (CERES)



Grise and Medeiros (submitted)

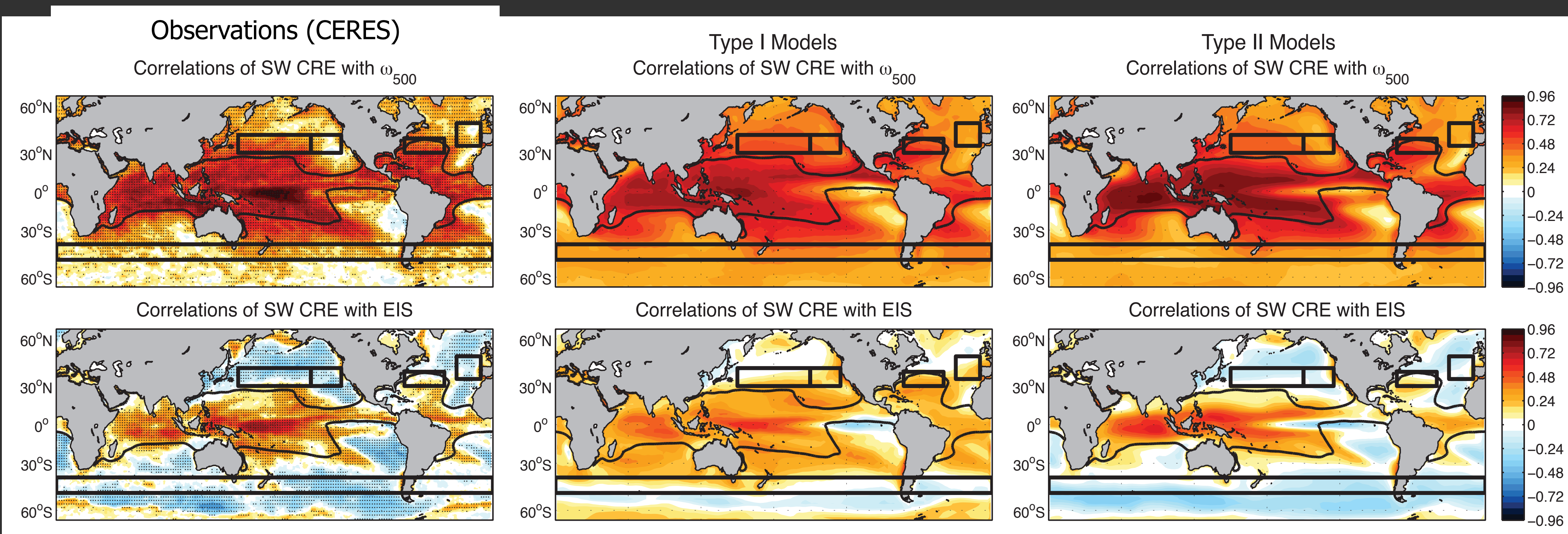
Understanding the model biases



Grise and Medeiros (submitted)

Biases in type I models appear related to overdependence of model cloud-radiative effects on vertical motion and underdependence of model cloud-radiative effects on lower tropospheric stability.

Understanding the model biases



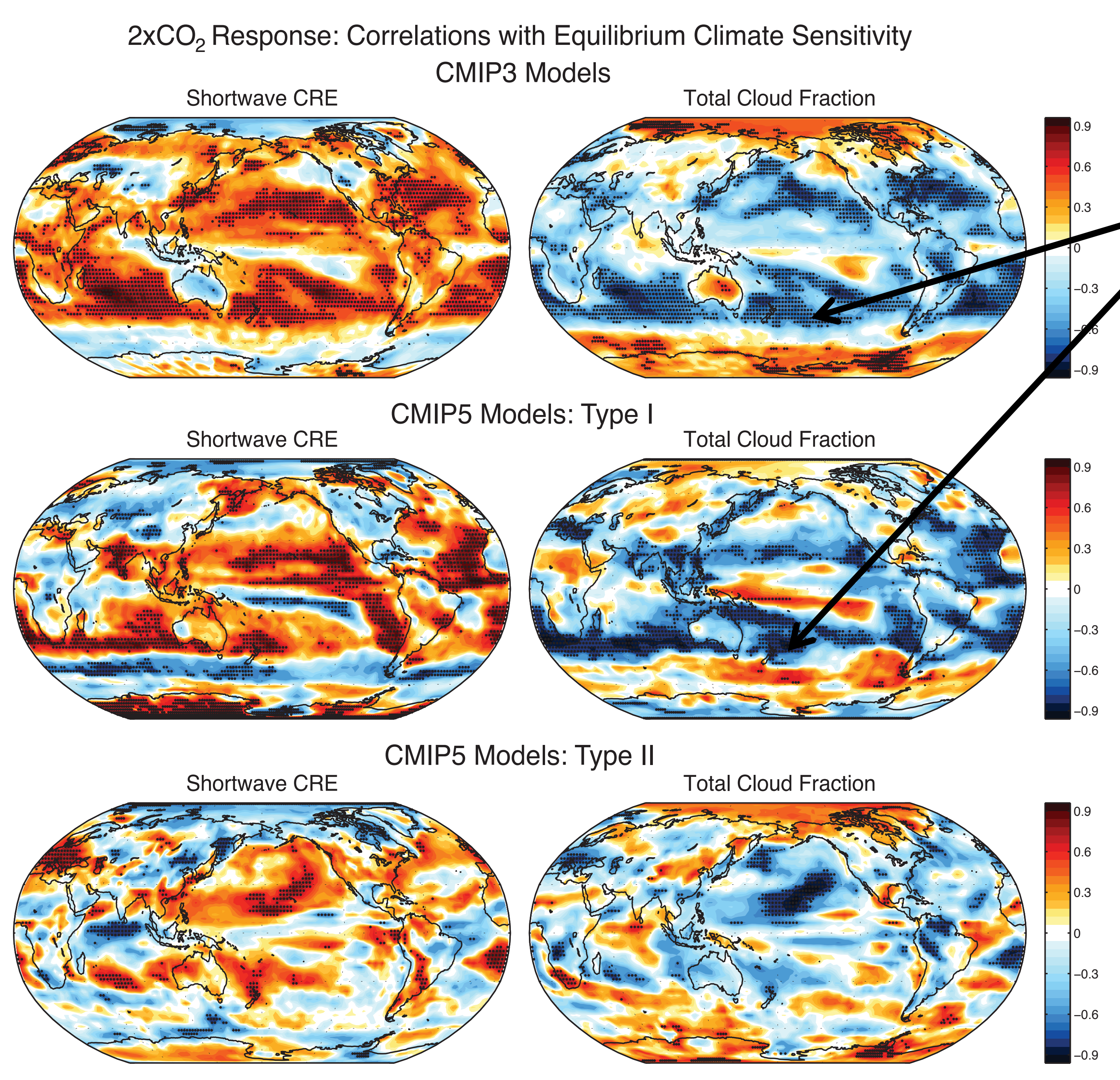
Grise and Medeiros (submitted)

Biases in type I models appear related to overdependence of model cloud-radiative effects on vertical motion and underdependence of model cloud-radiative effects on lower tropospheric stability.

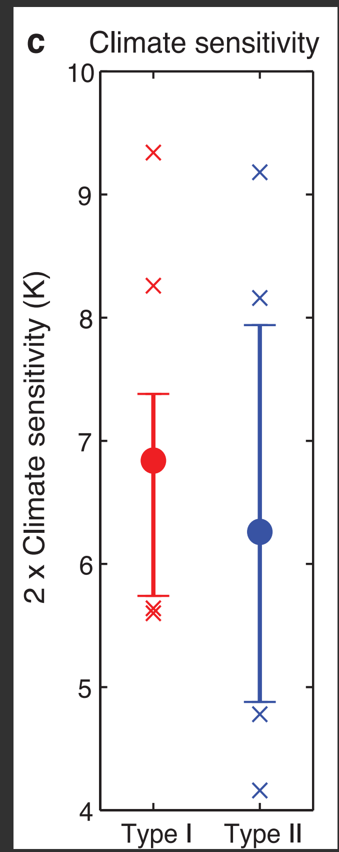
Qu et al. (2015) reach similar conclusion for subtropical clouds.

What are the implications for climate sensitivity?

Implications for Climate Sensitivity

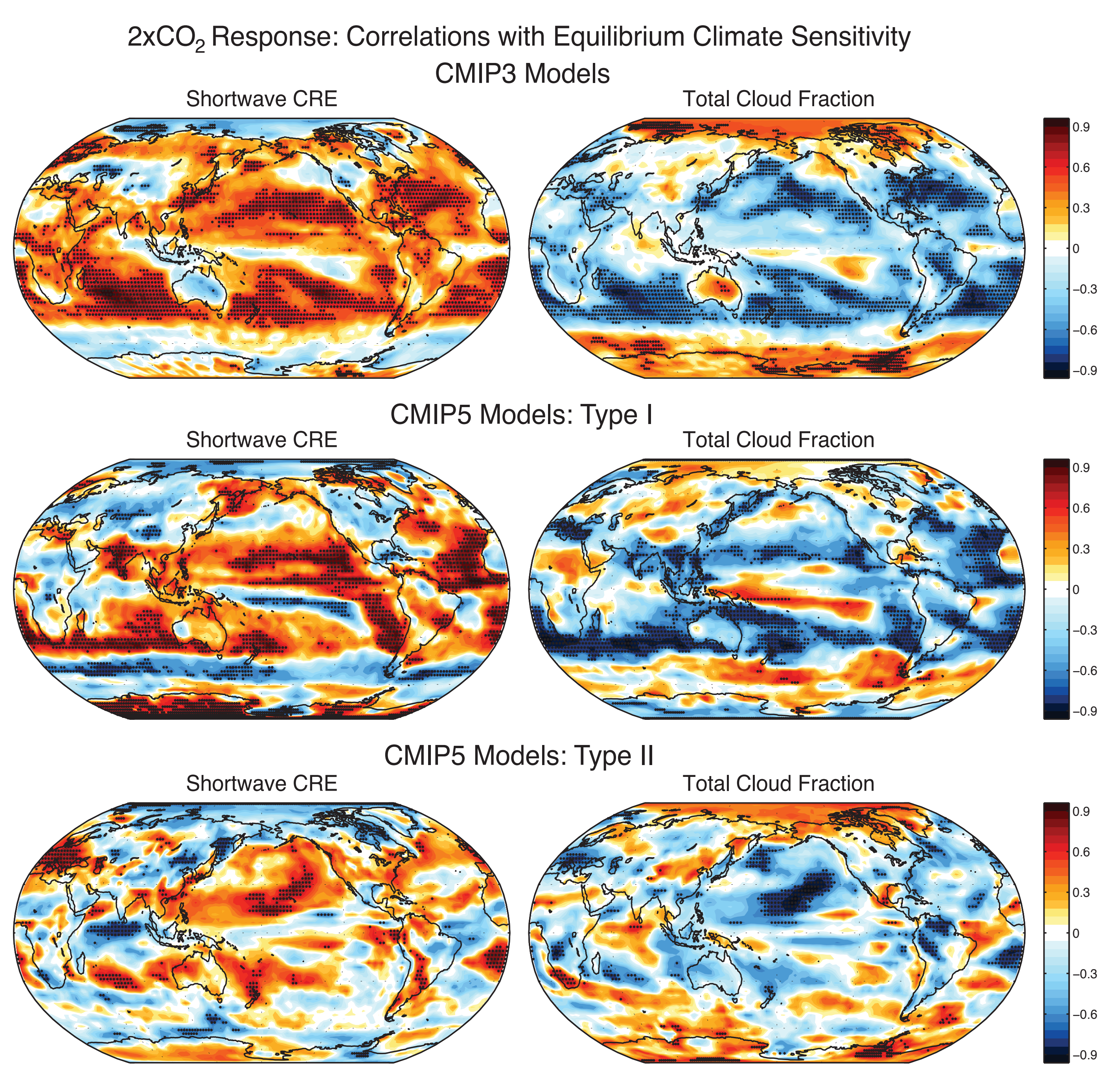


1) Significant correlations between cloud responses equatorward of SH mid-latitude jet and climate sensitivity in type I models.



adapted from Grise et al. (2015)

Implications for Climate Sensitivity

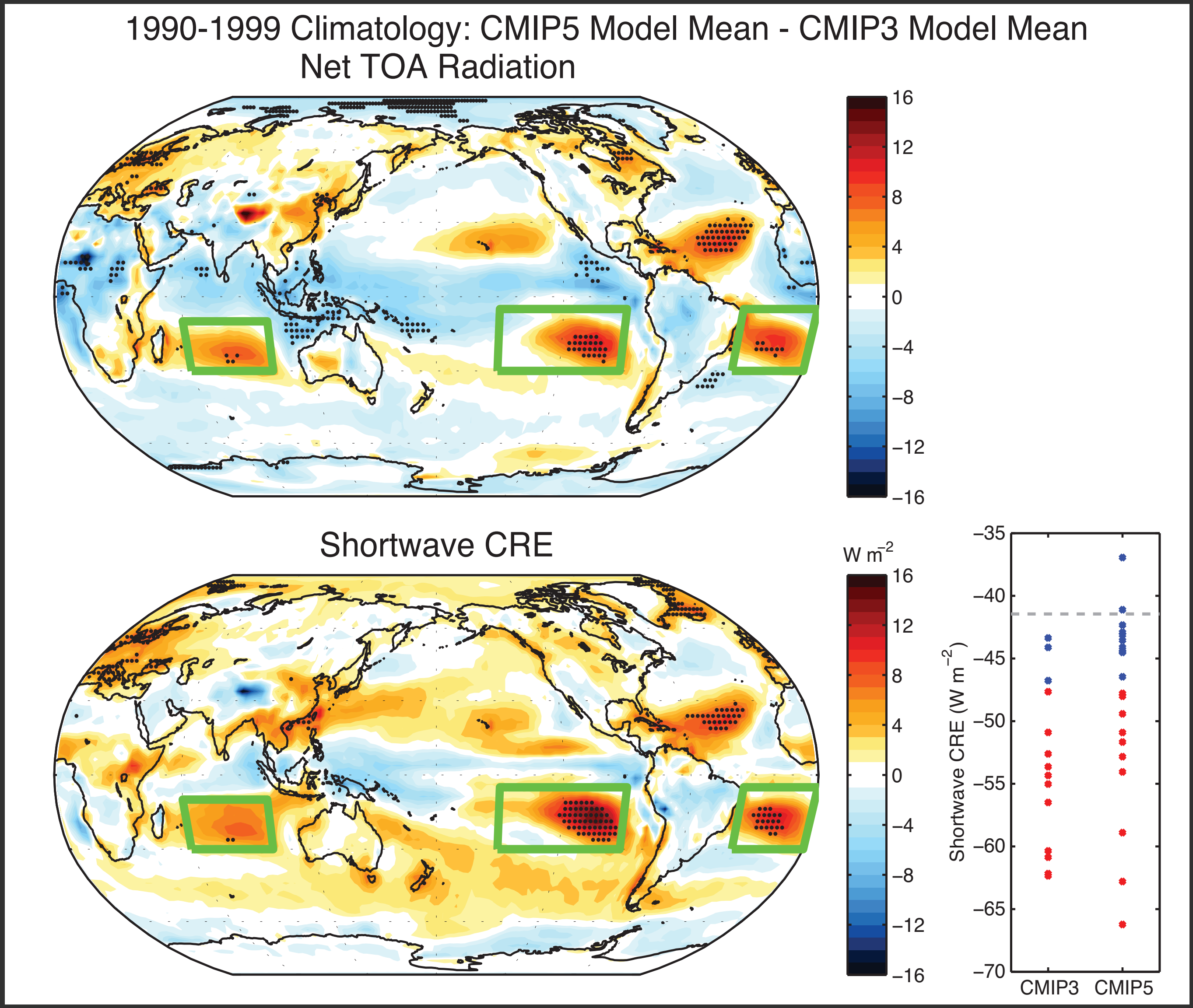


1) Significant correlations between cloud responses equatorward of SH mid-latitude jet and climate sensitivity in type I models.

2) Correlations also extend into the subtropics!

adapted from Grise et al. (2015)

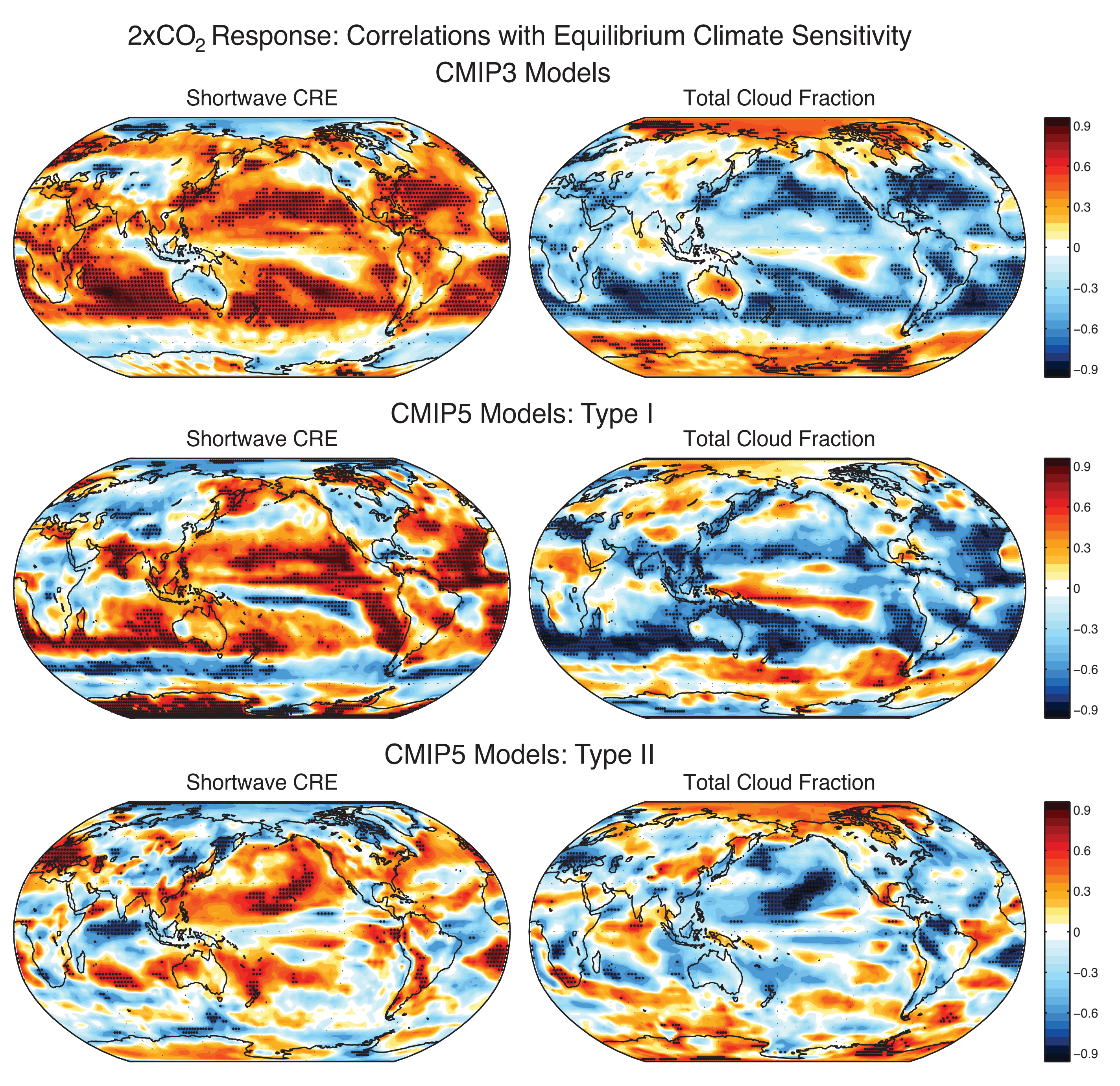
What's different in CMIP5 models?



Grise et al. (2015)

Largest improvements in net radiation and shortwave cloud-radiative effect occurred over SH subtropical regions, not Southern Ocean.

Implications for Climate Sensitivity

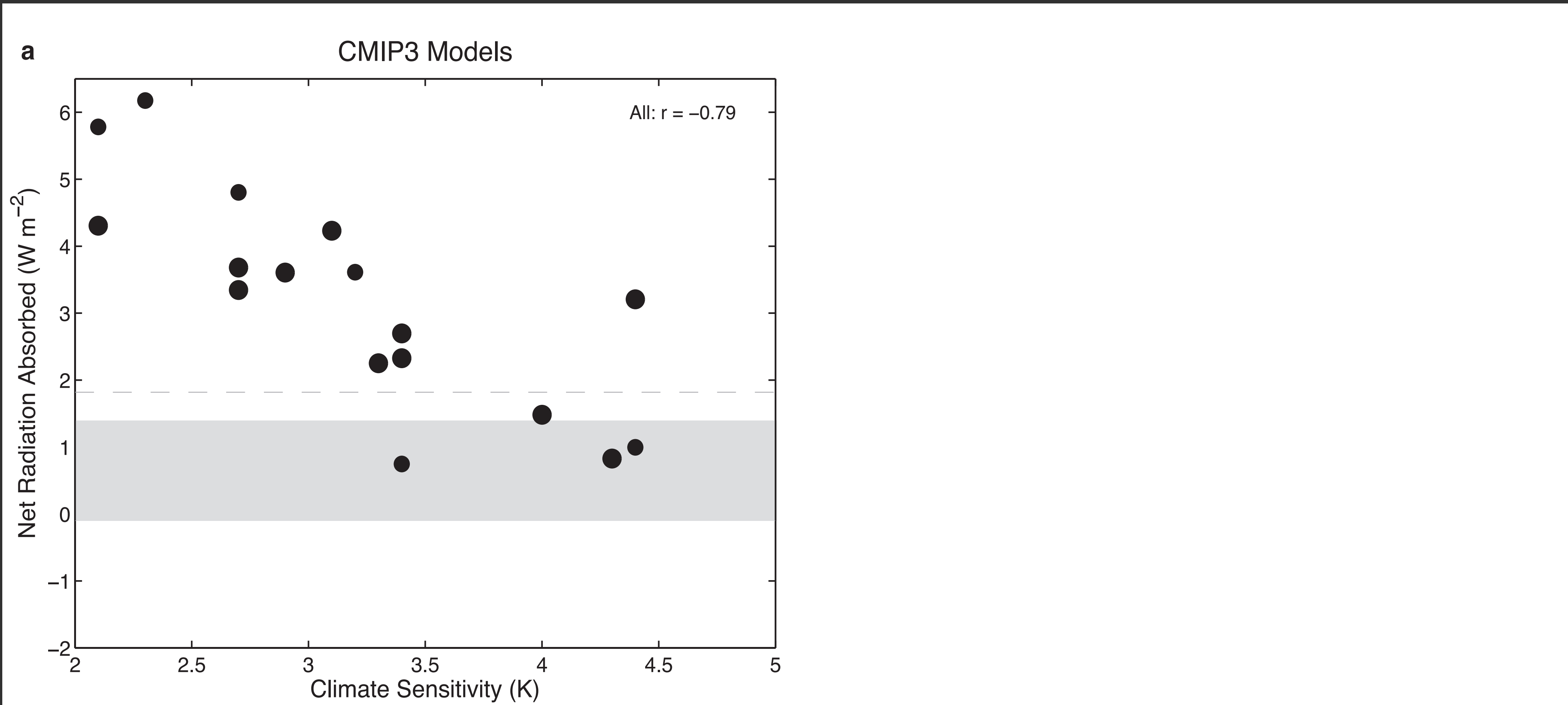


1) Significant correlations between cloud responses equatorward of SH mid-latitude jet and climate sensitivity in type I models.

2) Correlations also extend into the subtropics!
   - Brighter clouds in present-day climatology
   - Greater warming with cloud fraction reduction

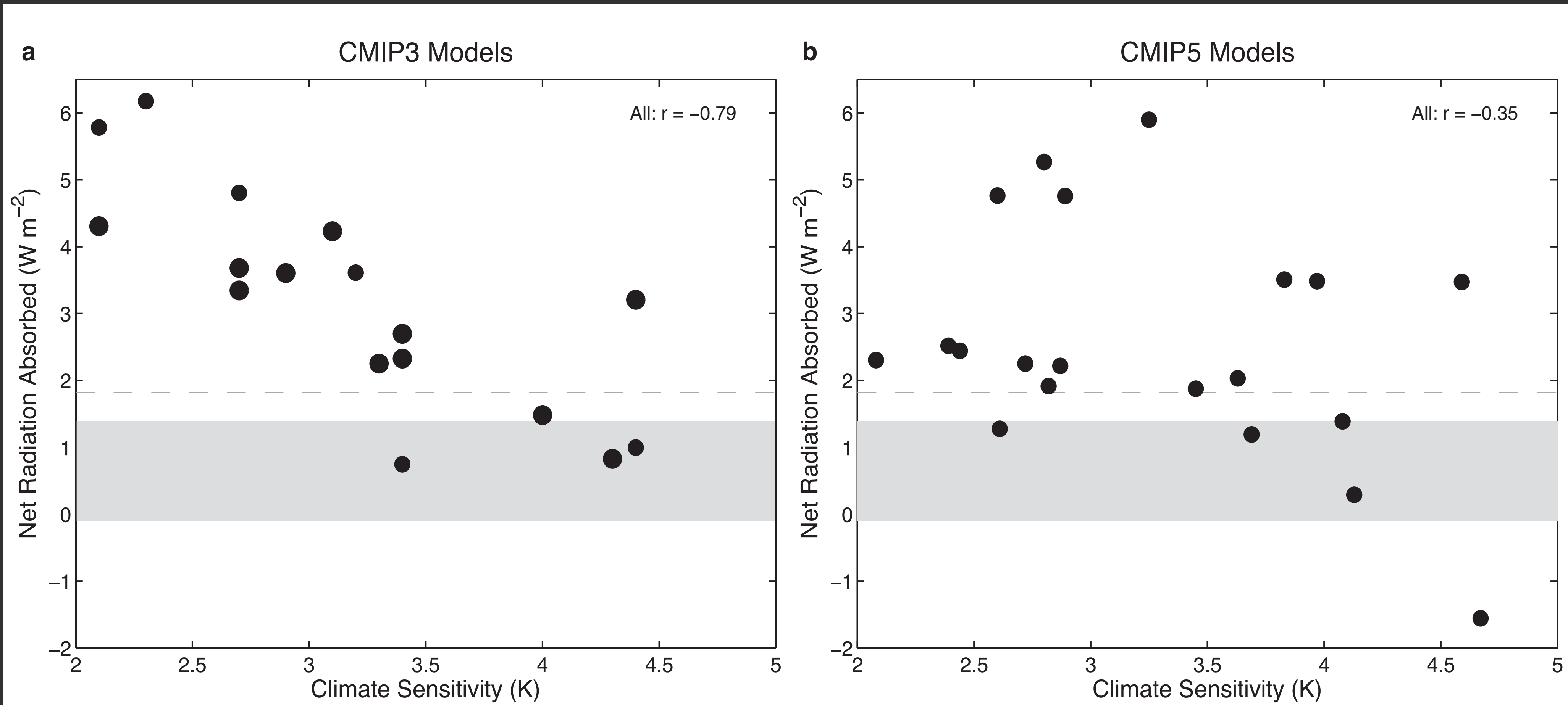
adapted from Grise et al. (2015)

Implications for Climate Sensitivity



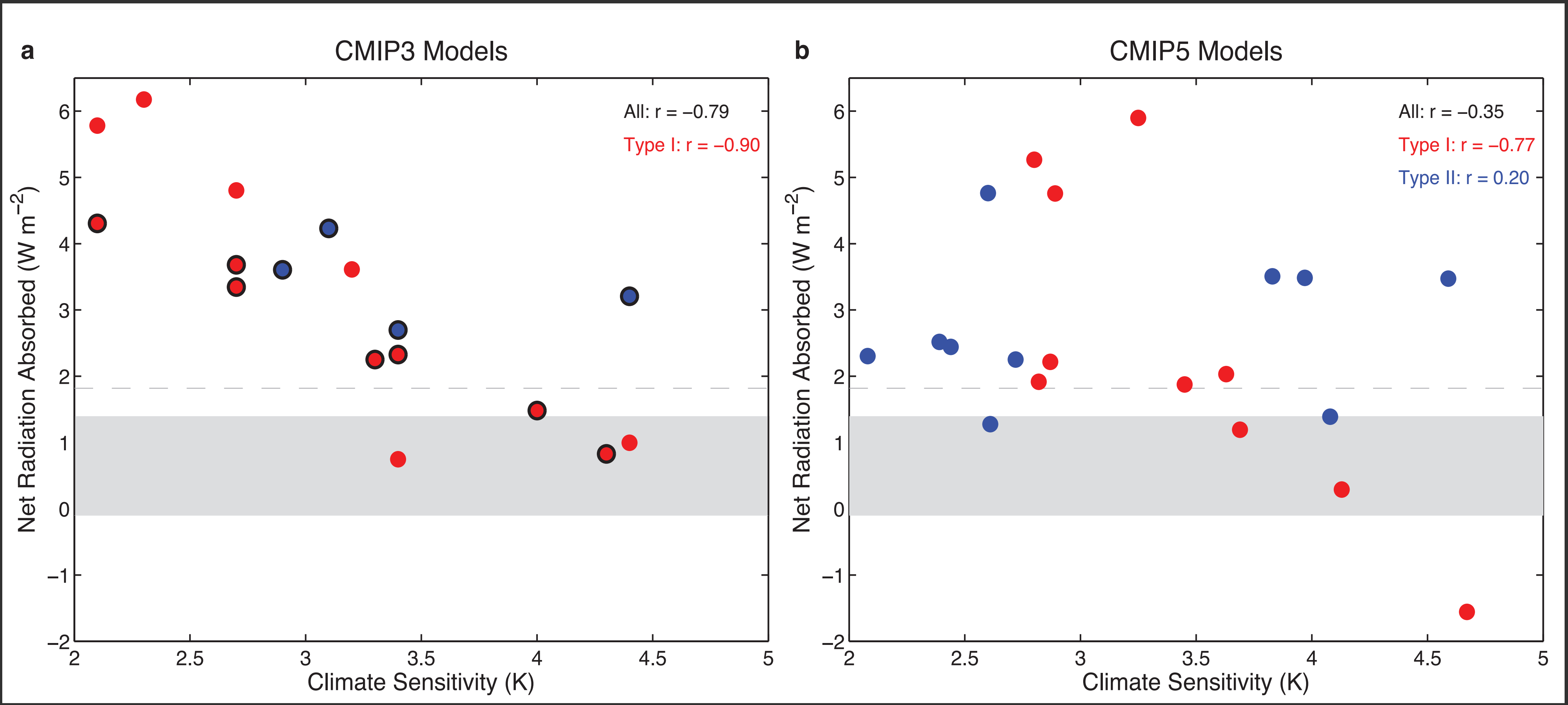
CMIP3 models with most realistic values of present-day Southern Hemisphere net TOA radiation have highest climate sensitivity. (Trenberth & Fasullo 2010)

Implications for Climate Sensitivity



This relationship disappears in CMIP5 models! (Grise et al. 2015)

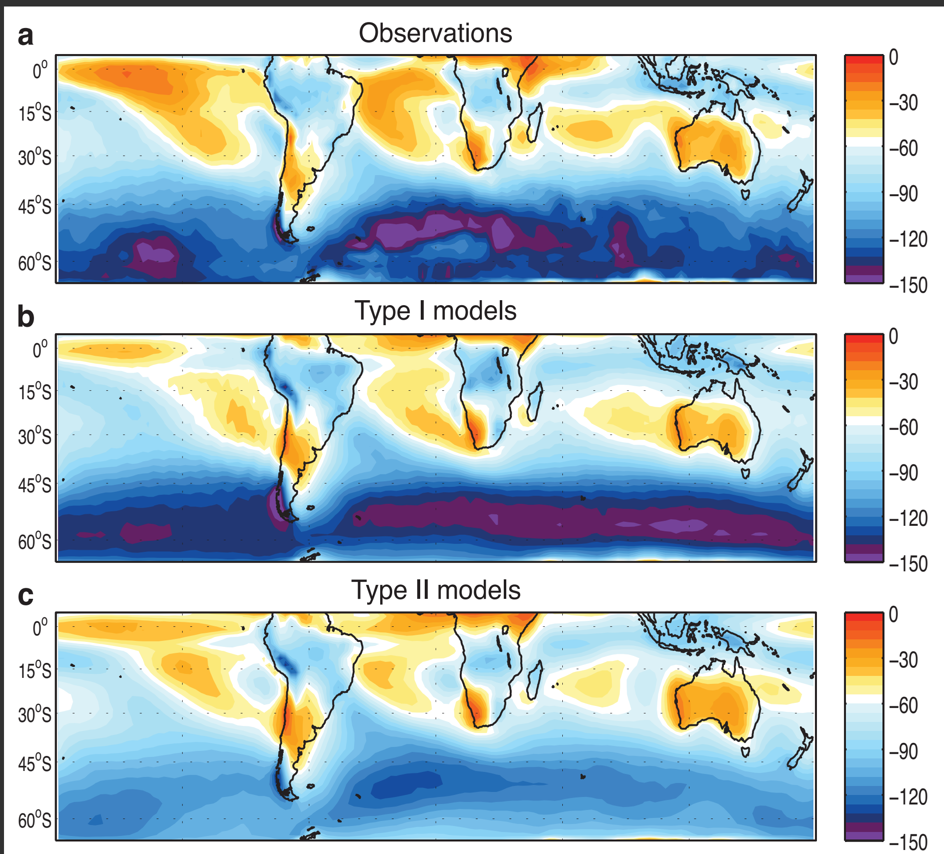
Implications for Climate Sensitivity



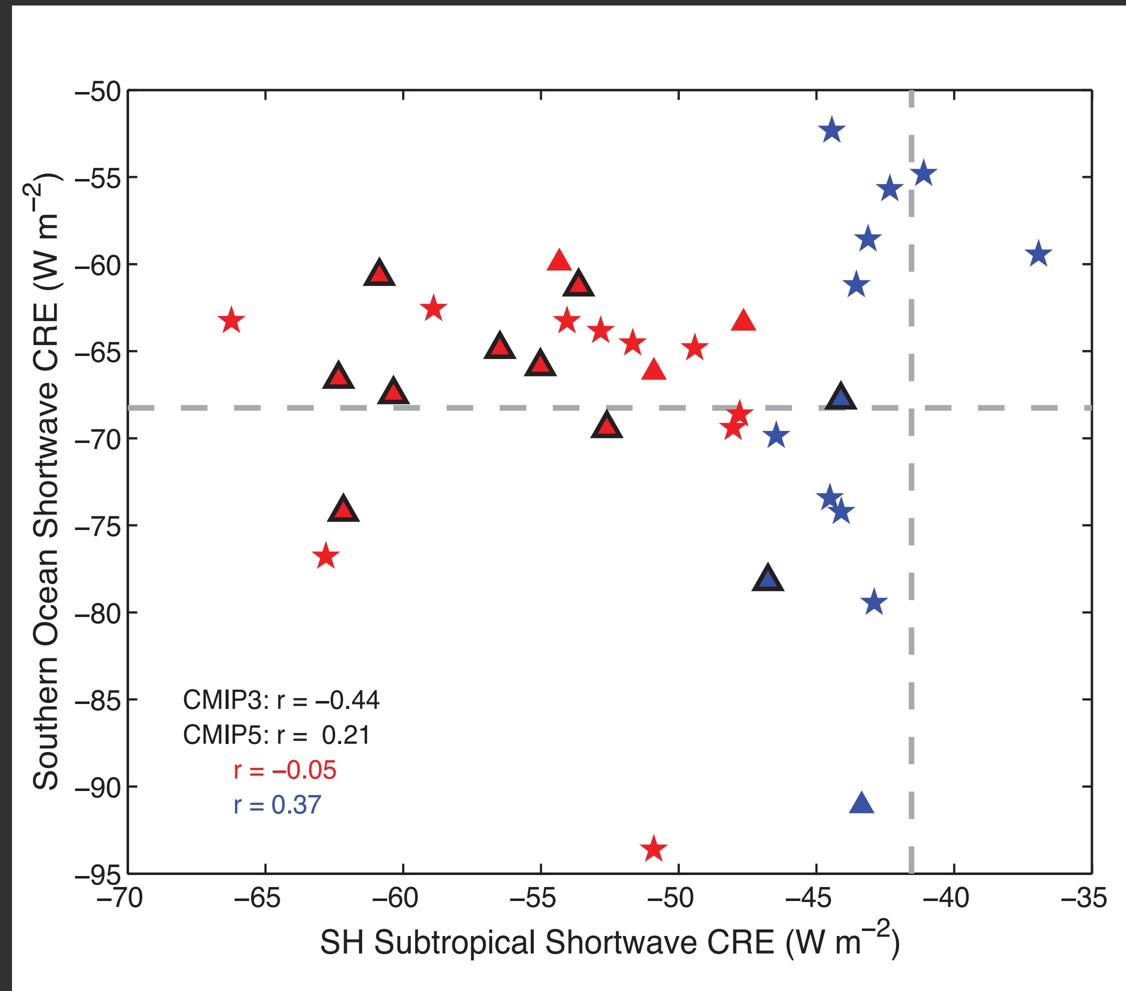
This relationship disappears in CMIP5 models! (Grise et al. 2015)

The correlations between SH radiation biases and climate sensitivity arise primarily from Type I models.

Present-Day Shortwave CRE Biases: Southern Ocean vs. SH Subtropics



Grise and Polvani (2014)



Grise et al. (2015)

Trade-off in CMIP models between representation of subtropical clouds and Southern Ocean clouds

Conclusions

Today's Questions

1) Has the recent poleward shift in the Southern Hemisphere mid-latitude jet contributed to cloud feedbacks?

Many climate models indicate that the poleward shift in the jet may have a positive (warming) feedback on Earth's radiative budget through shifts and changes in cloud patterns. This is **not** supported by observations.

Today's Questions

2) Why are some climate models biased in representing this feedback? And, what are the implications for climate sensitivity?

The shortwave cloud-radiative effect response to the recent poleward jet shift in the Southern Hemisphere is likely overestimated by the CMIP5 multi-model mean. This is due to the overdependence of model cloud-radiative effects on vertical velocity.

This effect was strongly correlated with the spread in climate sensitivity in older CMIP models.

Questions??

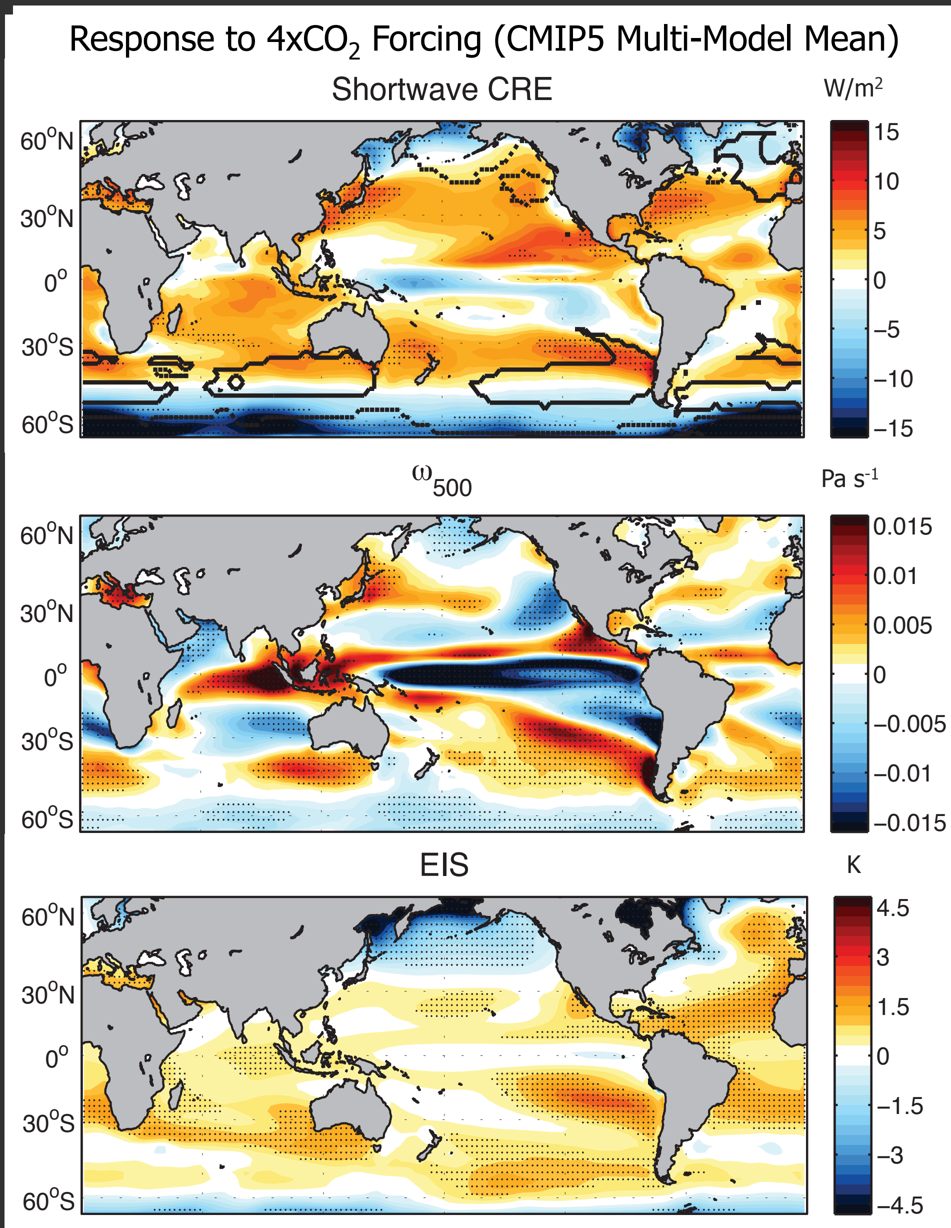
Grise, K. M., L. M. Polvani, G. Tselioudis, Y. Wu, and M. D. Zelinka, 2013: The ozone hole indirect effect: Cloud-radiative anomalies accompanying the poleward shift of the eddy-driven jet in the Southern Hemisphere. *Geophys. Res. Lett.*, **40**, 3688–3692.

Grise, K. M., and L. M. Polvani, 2014: Southern Hemisphere cloud-dynamics biases in CMIP5 models and their implications for climate projections. *J. Climate*, **27**, 6074–6092.

Grise, K. M., L. M. Polvani, and J. T. Fasullo, 2015: Re-examining the relationship between climate sensitivity and the Southern Hemisphere radiation budget in CMIP models. *J. Climate*, **28**, 9298-9312.

Grise, K. M., and B. Medeiros, 2016: Understanding the varied influence of the mid-latitude jet on clouds and cloud-radiative effects in observations and global climate models. *J. Climate*, submitted.

Implications for Climate Sensitivity



Grise and Medeiros (submitted)

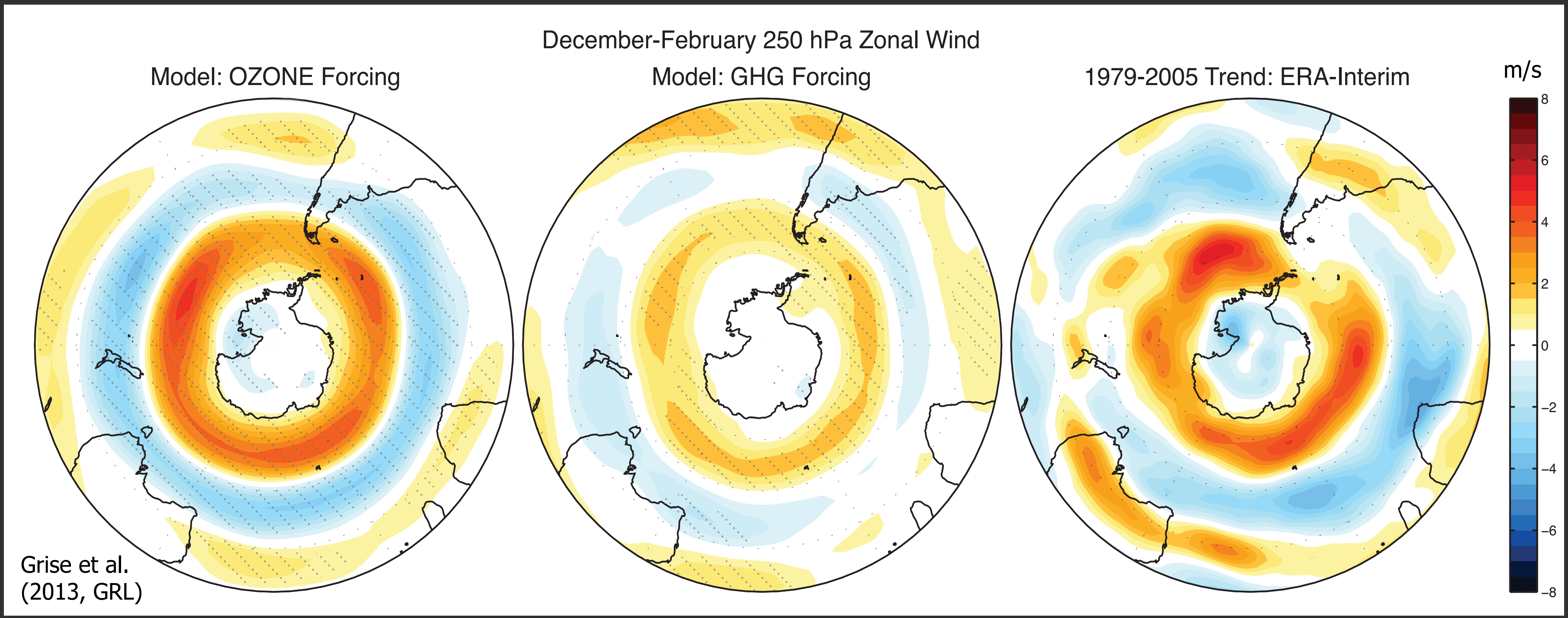
In response to increasing greenhouse gases, many climate models project similarly signed changes in lower tropospheric stability and vertical velocity over mid-latitude oceans.

We might expect a significant discrepancy in cloud feedbacks between type I and type II models in these regions.

Mid-Latitude Jet Shifts: 20th Century

- Over the late 20th century, the Southern Hemisphere mid-latitude jet has shifted poleward during the summer (DJF) season.

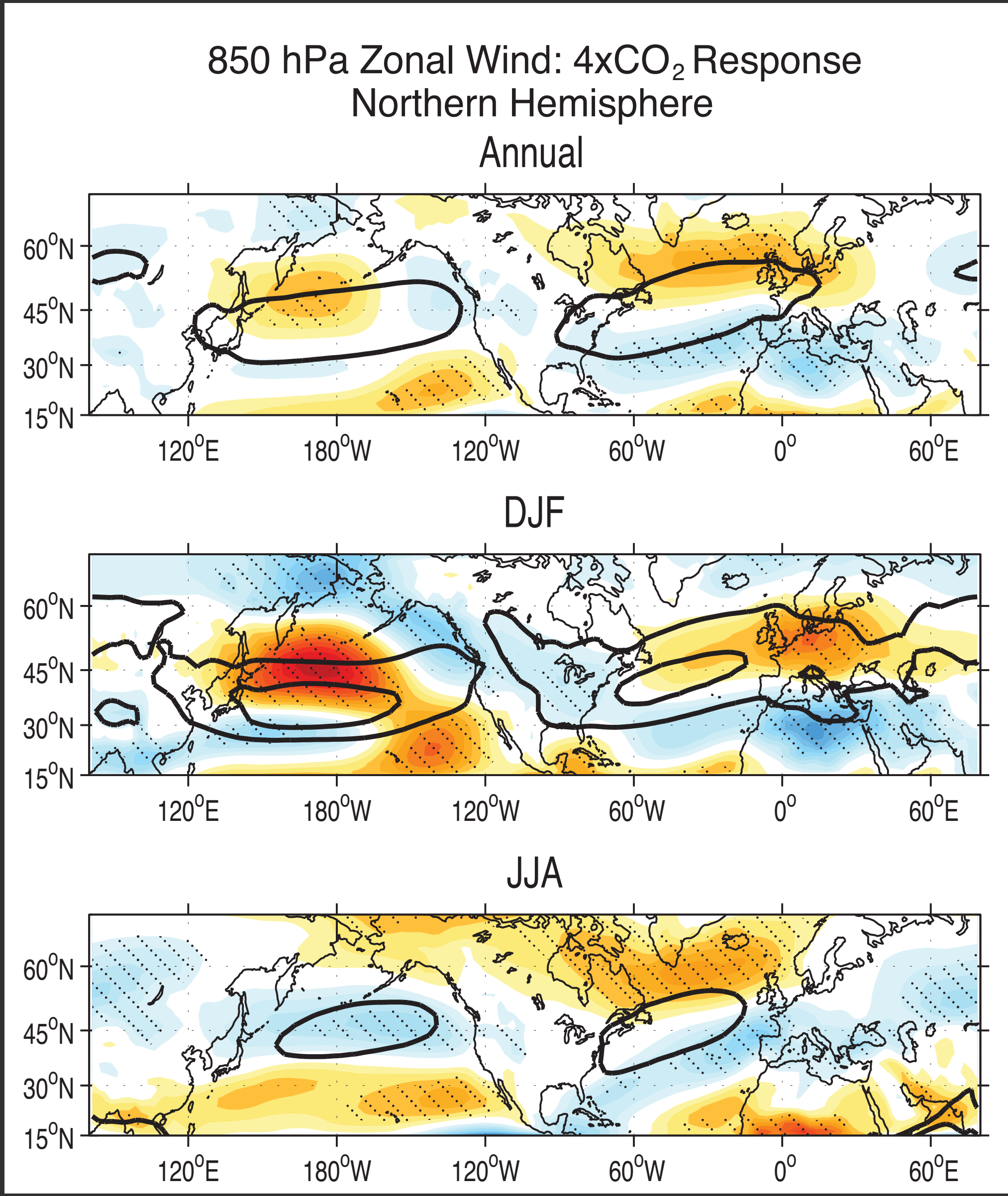
- Global climate models indicate that this shift was due, in large part, to the development of the Antarctic ozone hole.
  (Gillett and Thompson 2003; Polvani et al. 2011)



Mid-Latitude Jet Shifts: 21st Century

The projected response of the Northern Hemisphere mid-latitude jets to increasing greenhouse gases is **NOT** a simple poleward shift.

(Simpson et al. 2014; Grise and Polvani 2014, GRL)



Grise and Polvani (2014, GRL)

CAM3 Ozone Forcing

SPARC Ozone Dataset (Cionni et al. 2011)

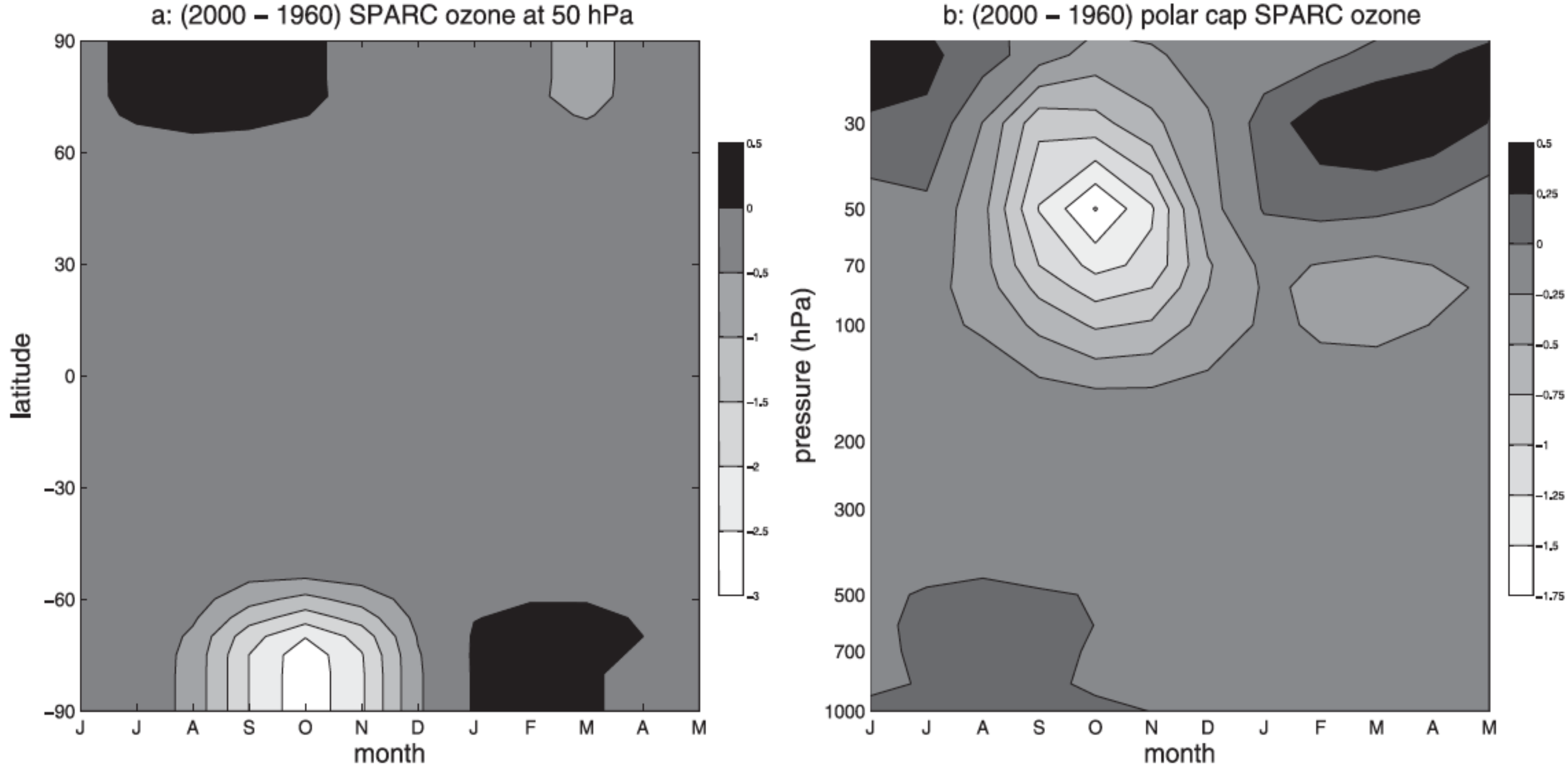
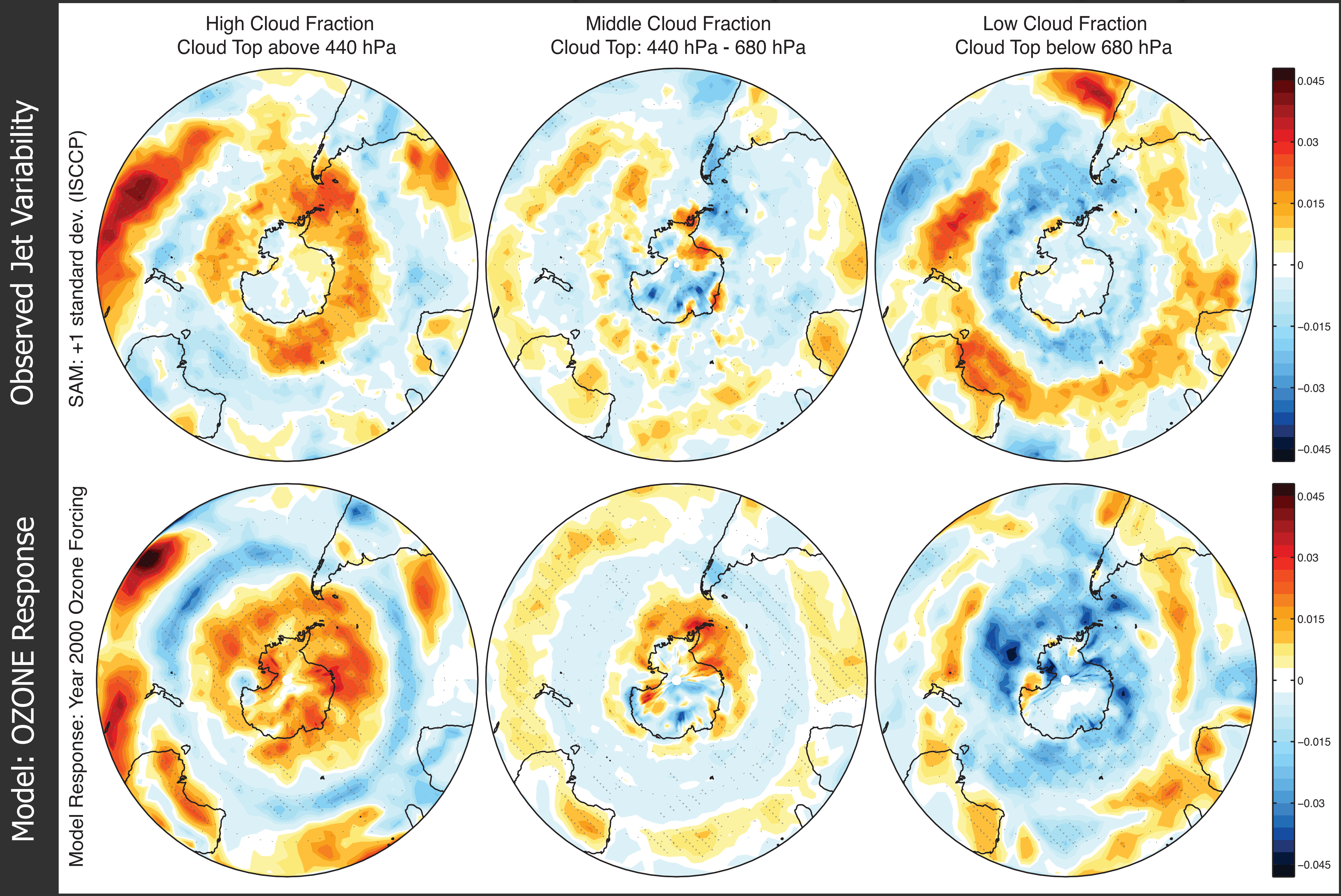


FIG. 1. The horizontal and vertical extents of the ozone hole used in the study, from the SPARC ozone dataset. (left) Latitudinal cross section at 50 hPa. (right) Vertical extent over the polar cap (defined as the area south of of 65°S). Units are ppmv. The ozone hole is the prominent white area in both panels.

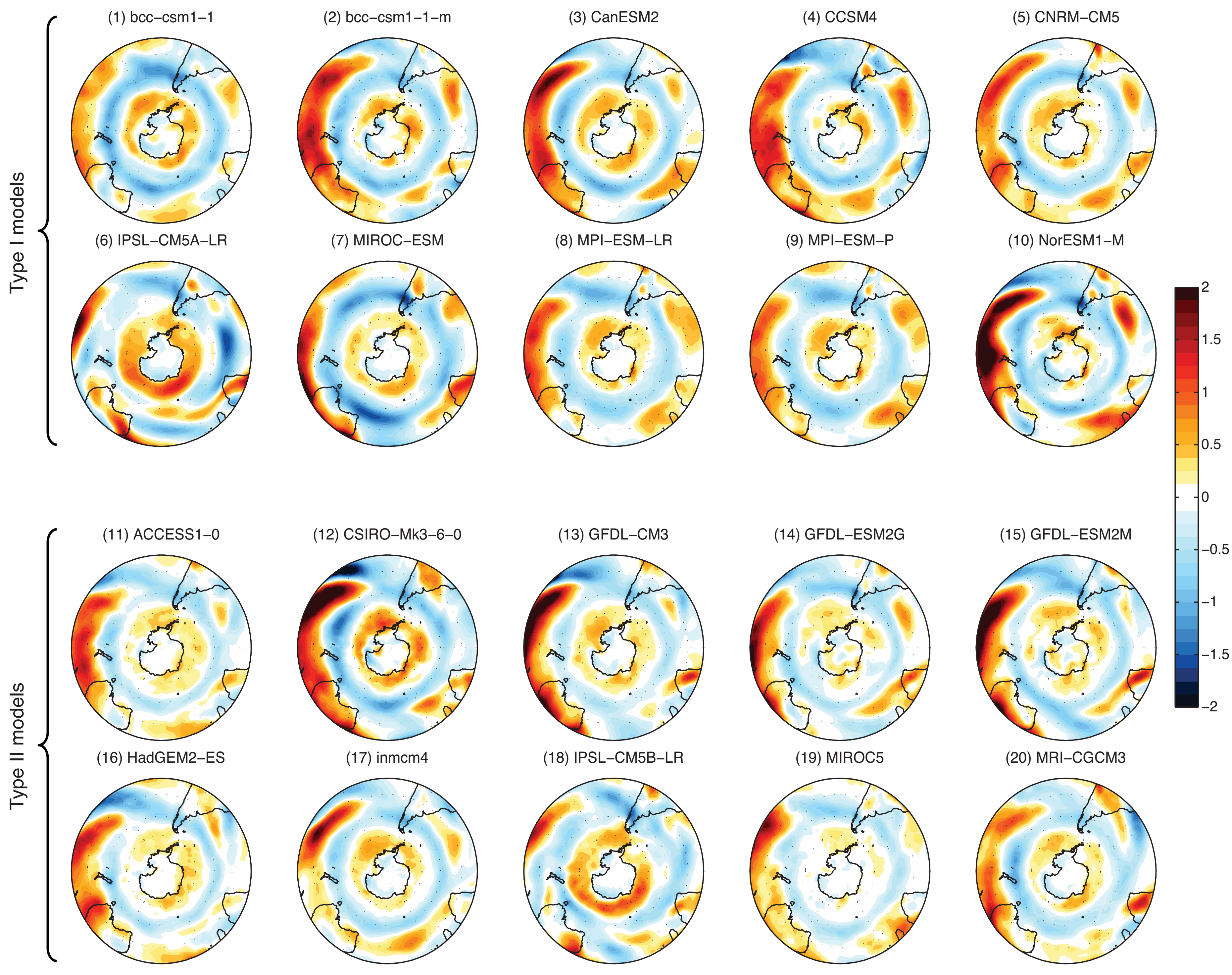
Polvani et al. (2011)

Are jet shifts associated with a cloud feedback?

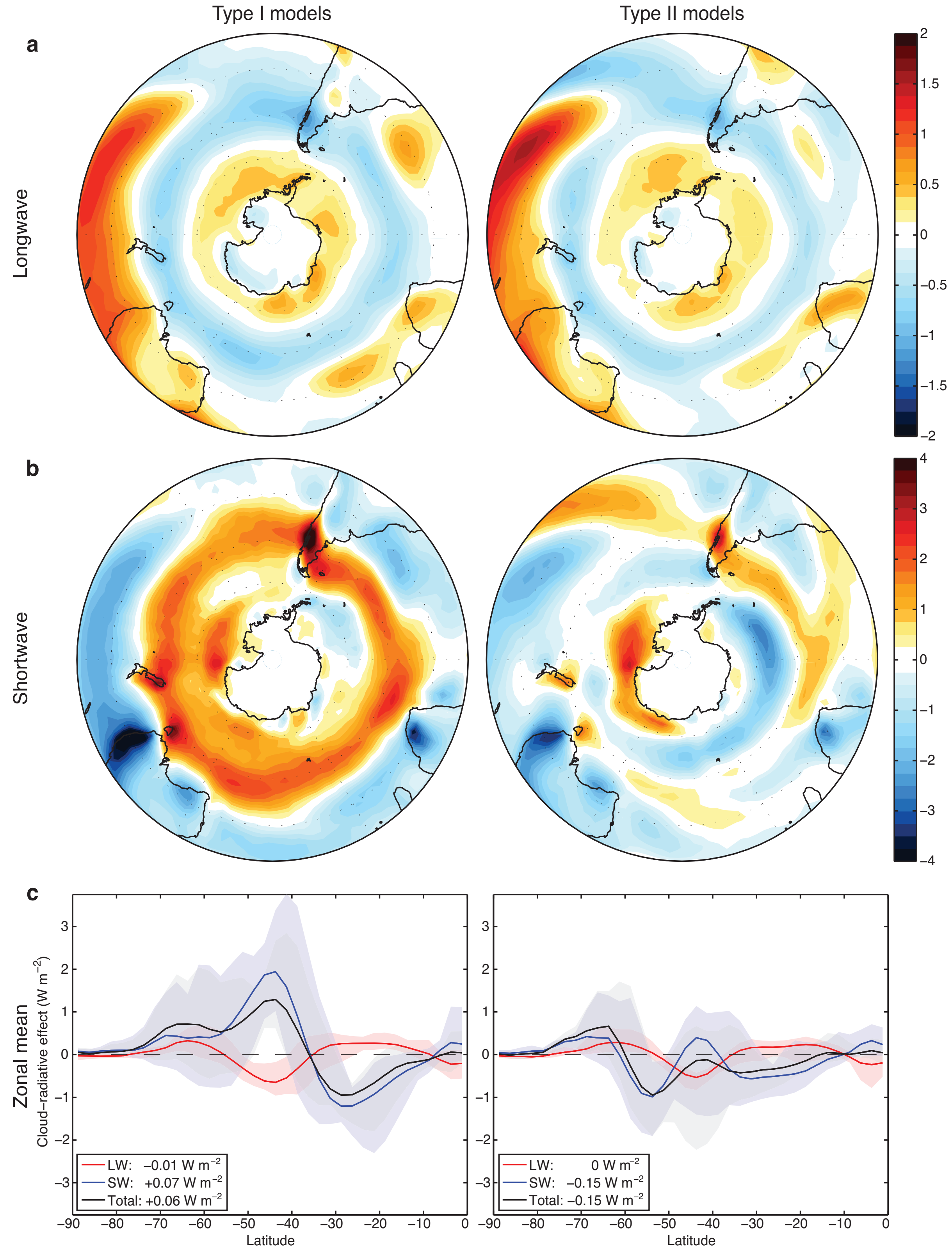
Method 1: Model Experiments (Grise et al. 2013, GRL)



Longwave Cloud Radiative Effect Anomalies for 1° Poleward Jet Shift

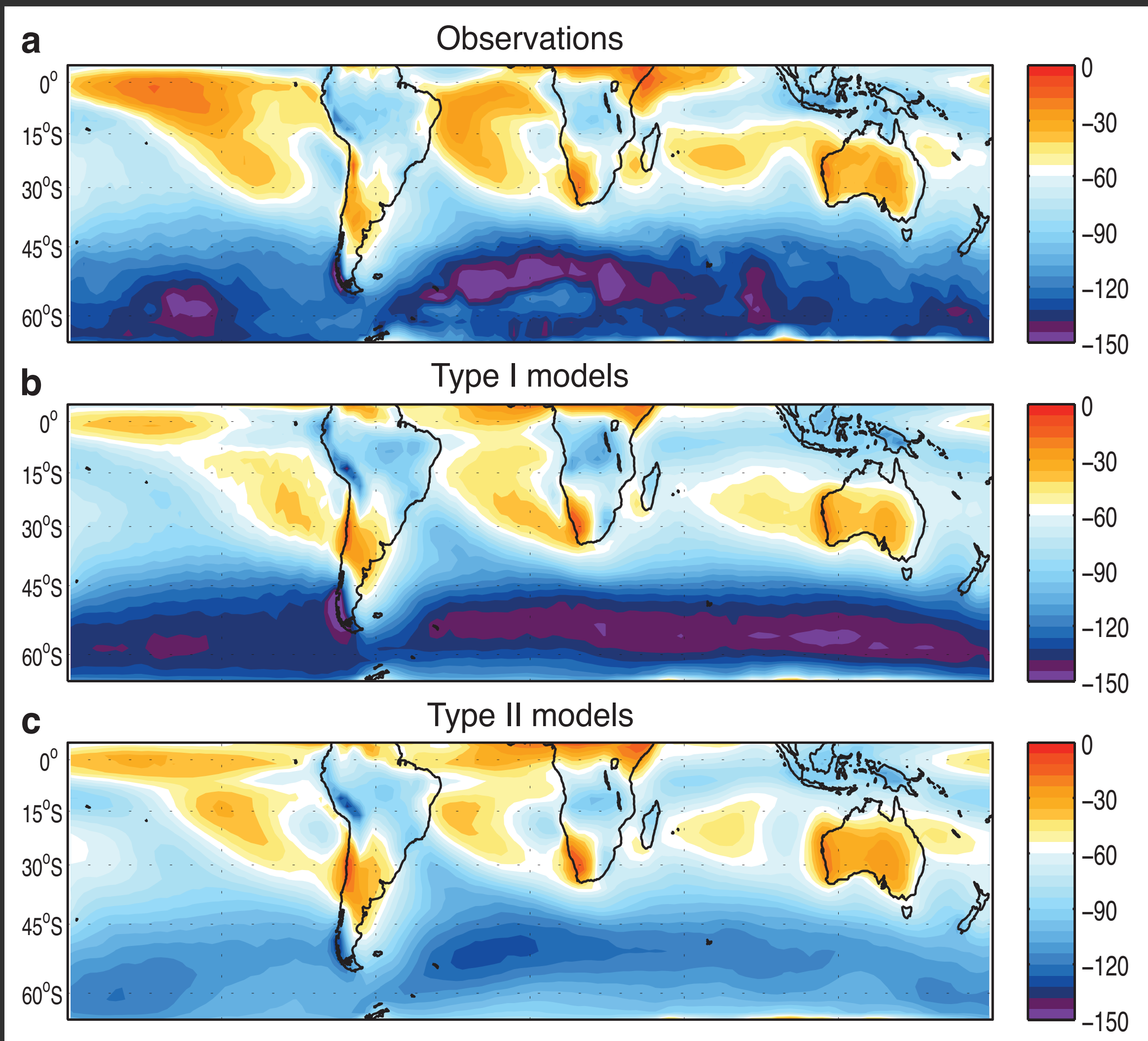


Composite Cloud-Radiative Effect Anomalies for 1° Poleward Jet Shift

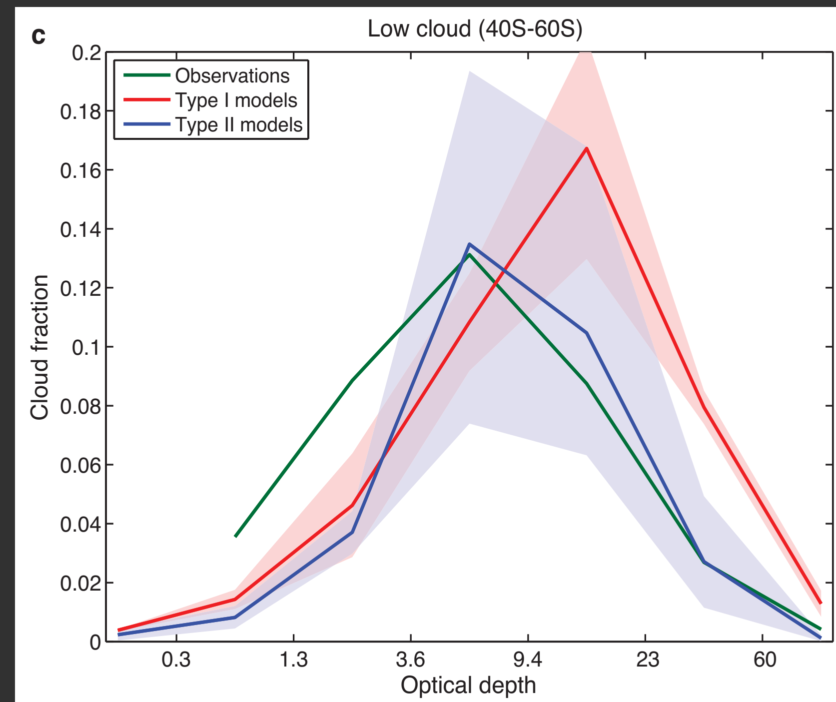


Why do the models behave so differently?

Shortwave Cloud-Radiative Effect Climatology



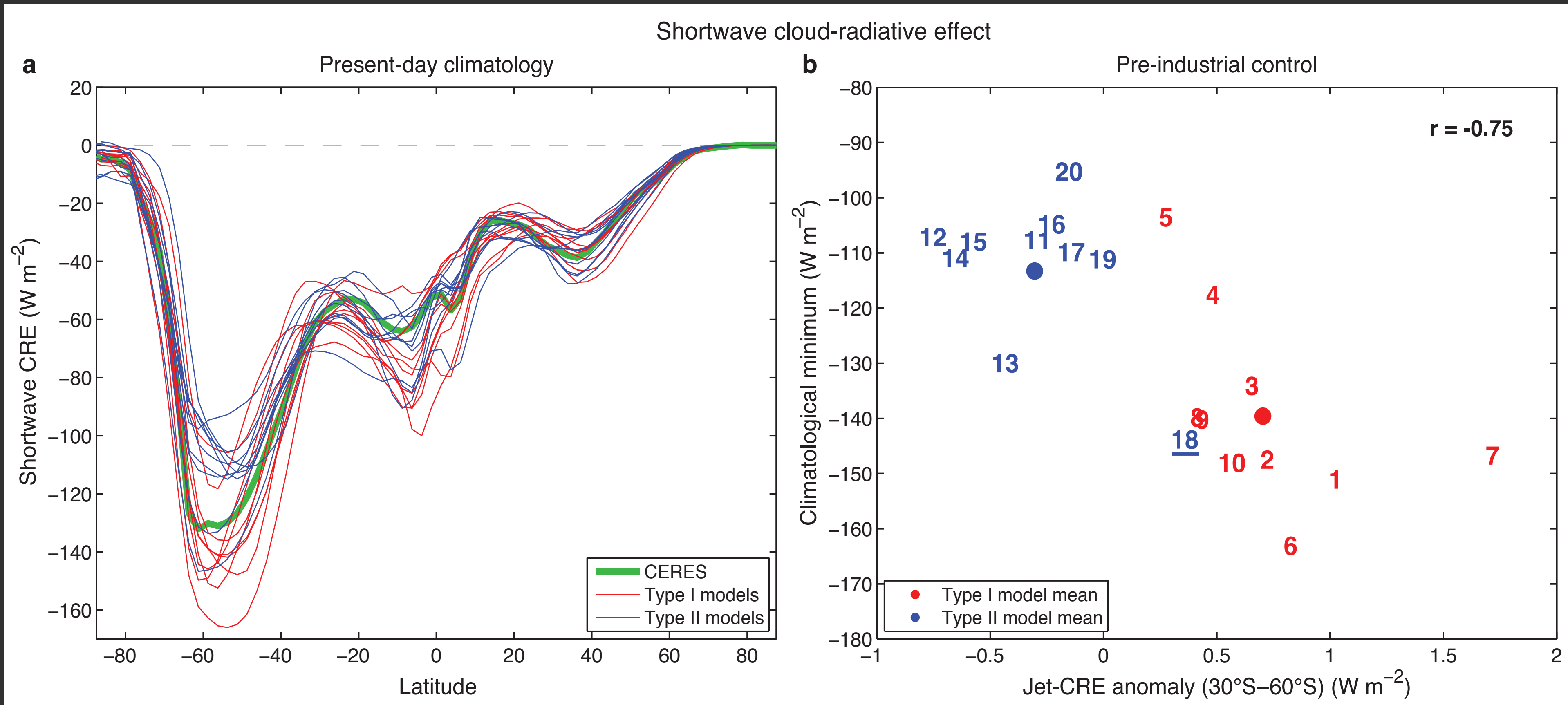
Cloud Fraction Climatology



Grise and Polvani (2014)

- <u>Type I models:</u> Bright, zonally symmetric Southern Ocean clouds
- <u>Type II models:</u> Less bright, more zonally asymmetric clouds

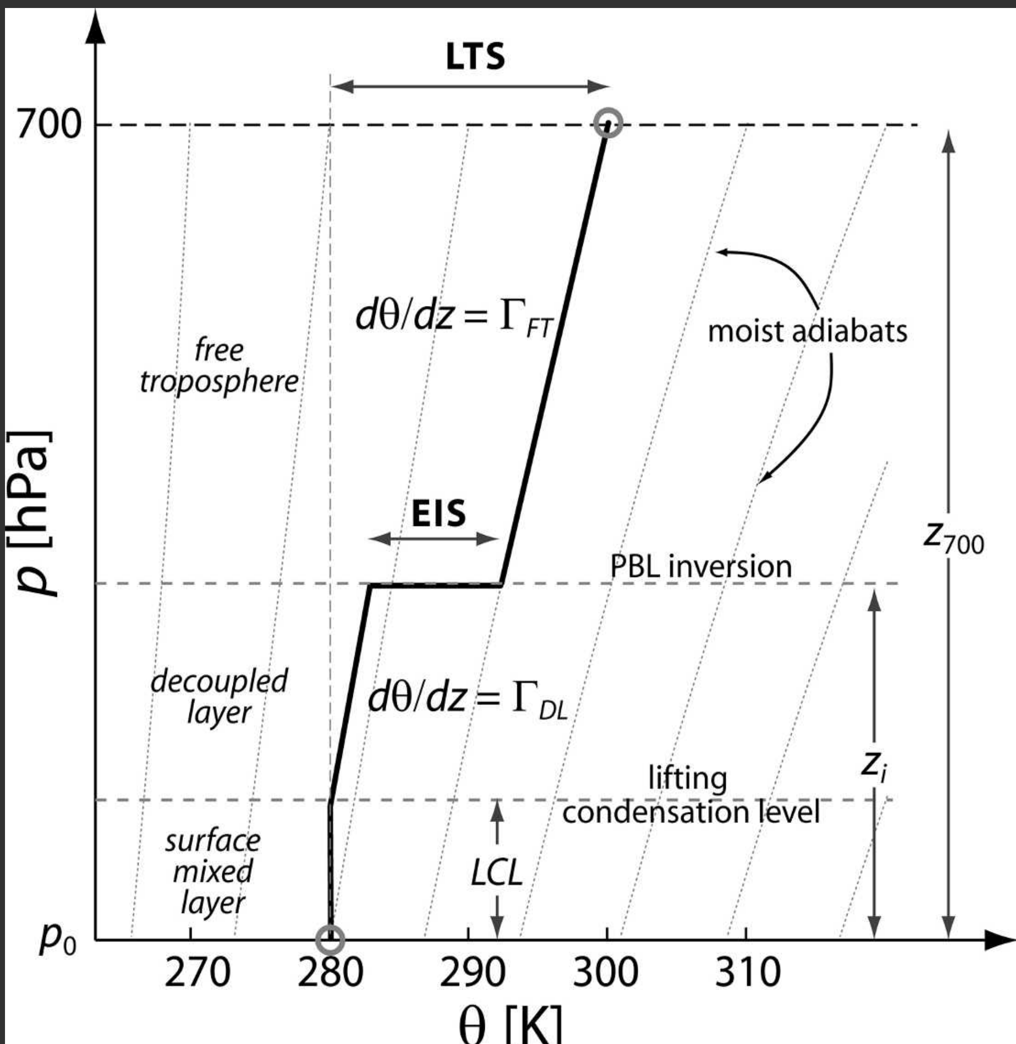
CMIP5 CRE Zonal Mean Climatology



Estimated Inversion Strength (EIS)

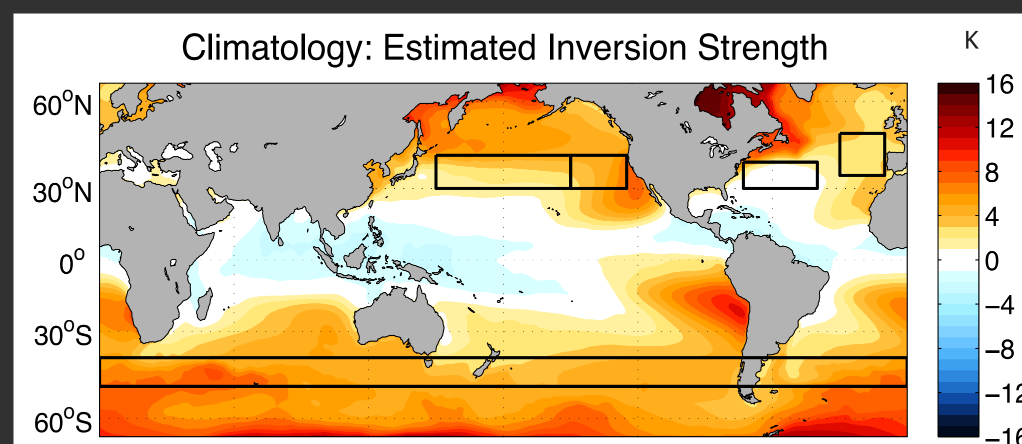
Wood and Bretherton (2006)

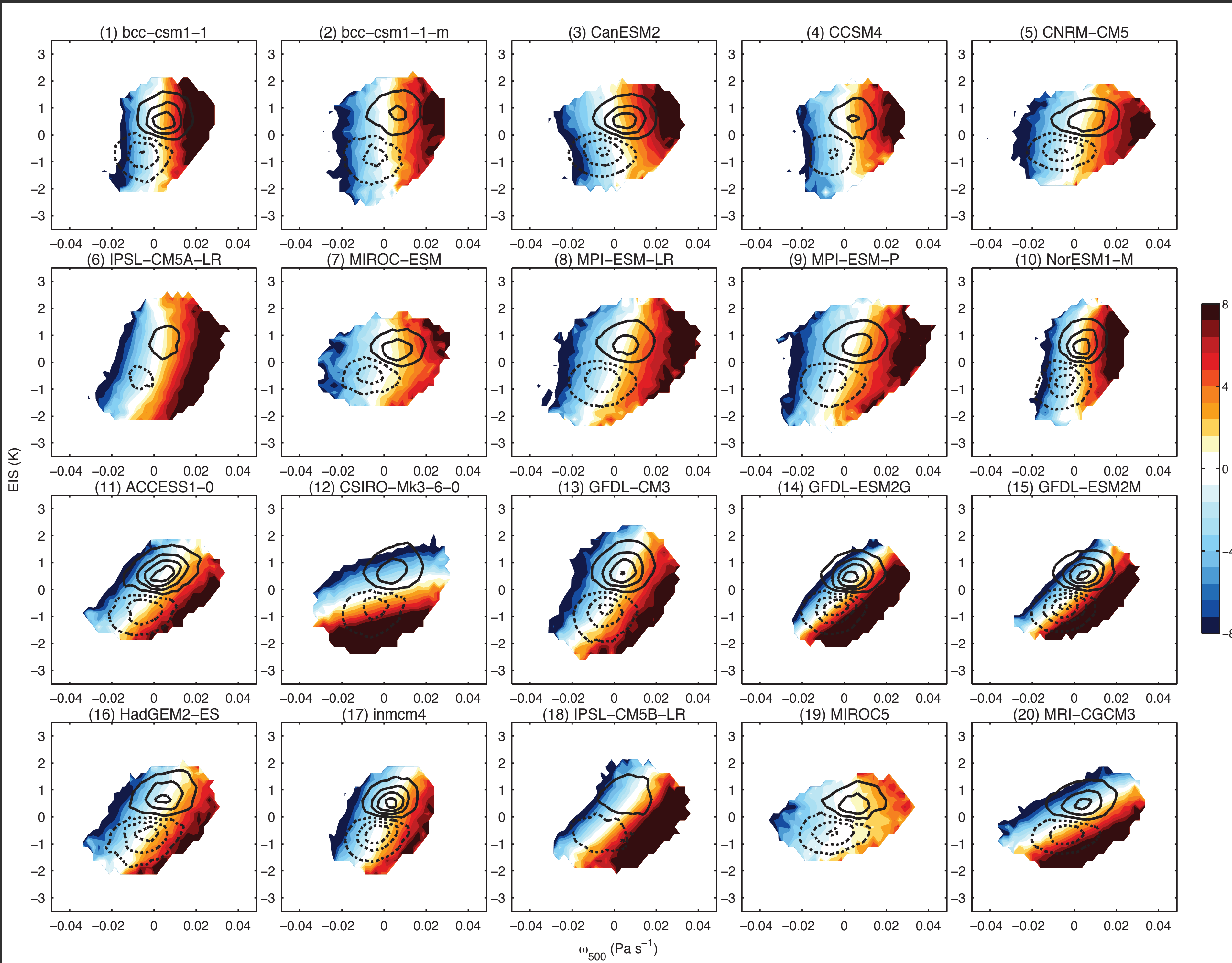
- $EIS = \theta_{700\ hPa} - \theta_{sfc} - \Gamma_{moist\ (850\ hPa)}\ (z_{700hPa} - z_{LCL})$



$\Delta\theta = \theta_{700\ hPa} - \theta_{sfc} - \Gamma_{FT}\ (z_{700} - z_i) - \Gamma_{DL}\ (z_i - LCL)$

$\Delta\theta = \theta_{700\ hPa} - \theta_{sfc} - \Gamma_{FT}\ z_{700} + \Gamma_{DL}\ LCL$

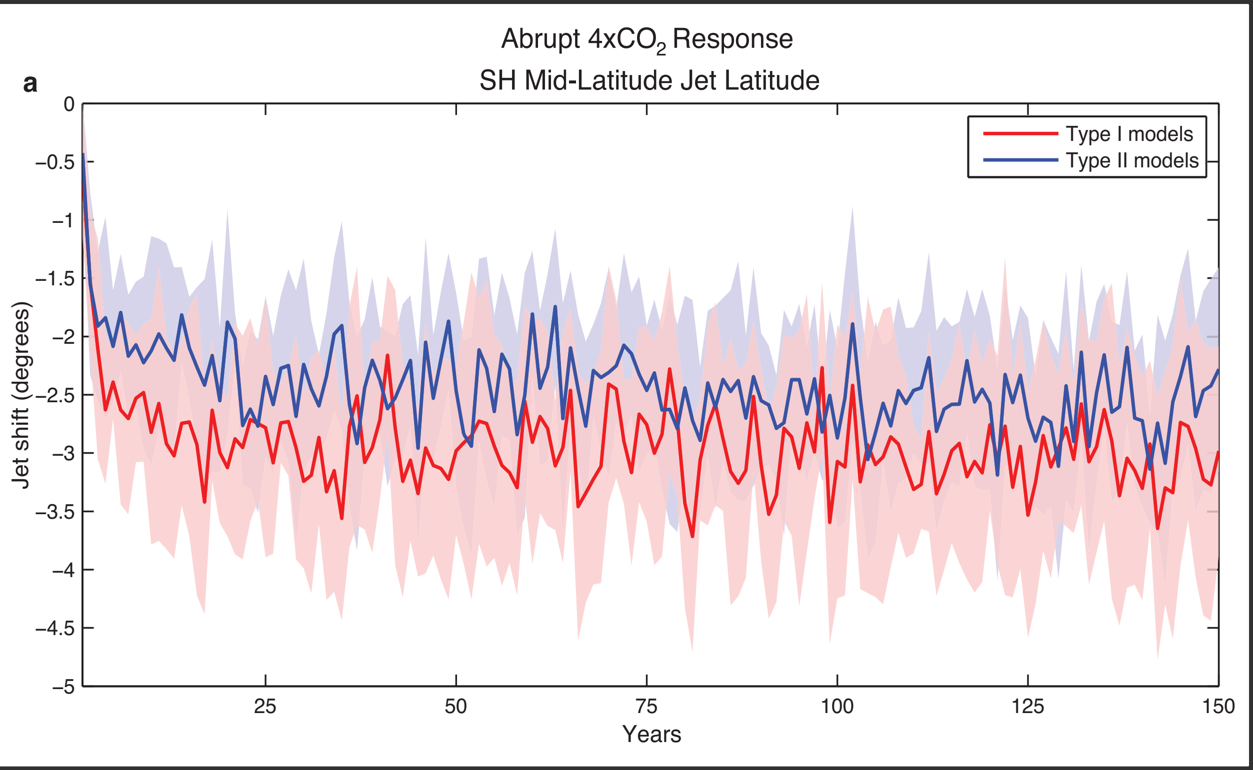



(1) bcc–csm1–1
(2) bcc–csm1–1–m
(3) CanESM2
(4) CCSM4
(5) CNRM–CM5
(6) IPSL–CM5A–LR
(7) MIROC–ESM
(8) MPI–ESM–LR
(9) MPI–ESM–P
(10) NorESM1–M
(11) ACCESS1–0
(12) CSIRO–Mk3–6–0
(13) GFDL–CM3
(14) GFDL–ESM2G
(15) GFDL–ESM2M
(16) HadGEM2–ES
(17) inmcm4
(18) IPSL–CM5B–LR
(19) MIROC5
(20) MRI–CGCM3
EIS (K)
ω_{500} (Pa s^{-1})
−0.04 −0.02 0 0.02 0.04
3 2 1 0 −1 −2 −3
8
4
0
−4
−8

Implications for Climate Change

Idealized Experiment: Abrupt Quadrupling of CO_2

1) Jet shifts rapidly poleward in both classes of CMIP5 models.



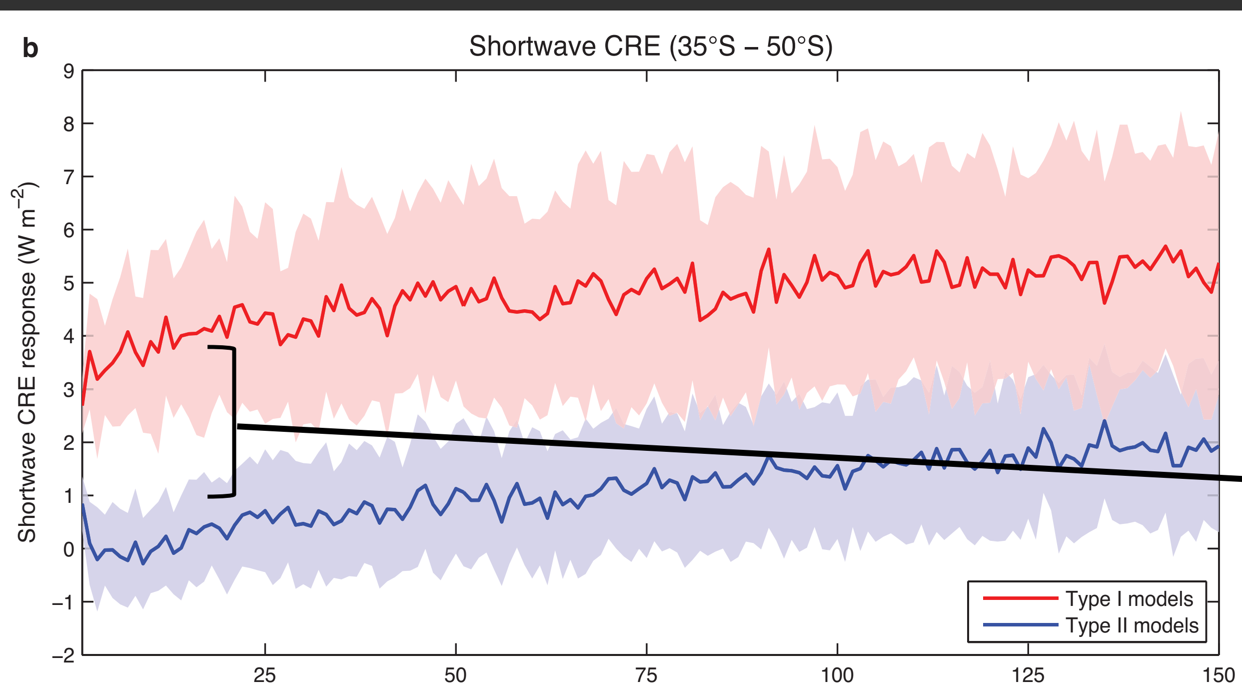
Grise and Polvani (2014, J. Climate)

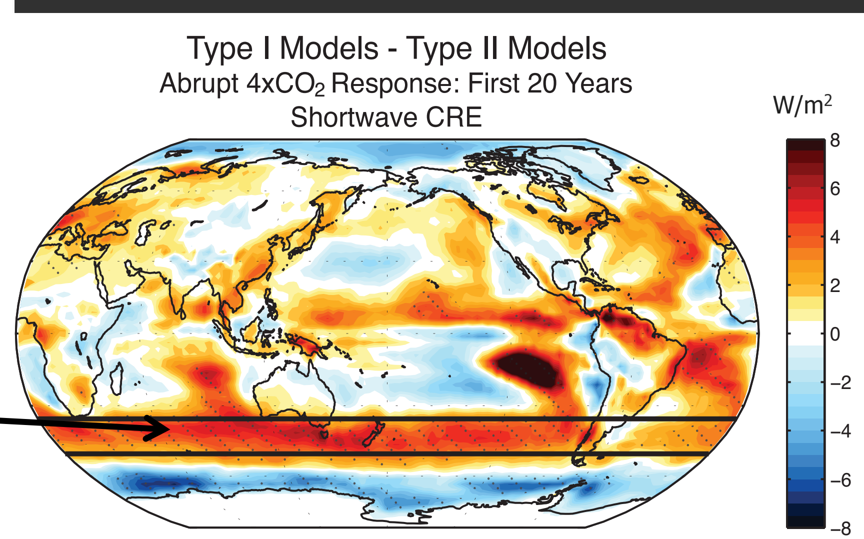
Implications for Climate Change

Idealized Experiment: Abrupt Quadrupling of CO_2

1) Jet shifts rapidly poleward in both classes of CMIP5 models.

2) Rapid reduction in reflection of shortwave radiation by clouds in Type I models only





Grise and Polvani (2014, J. Climate)

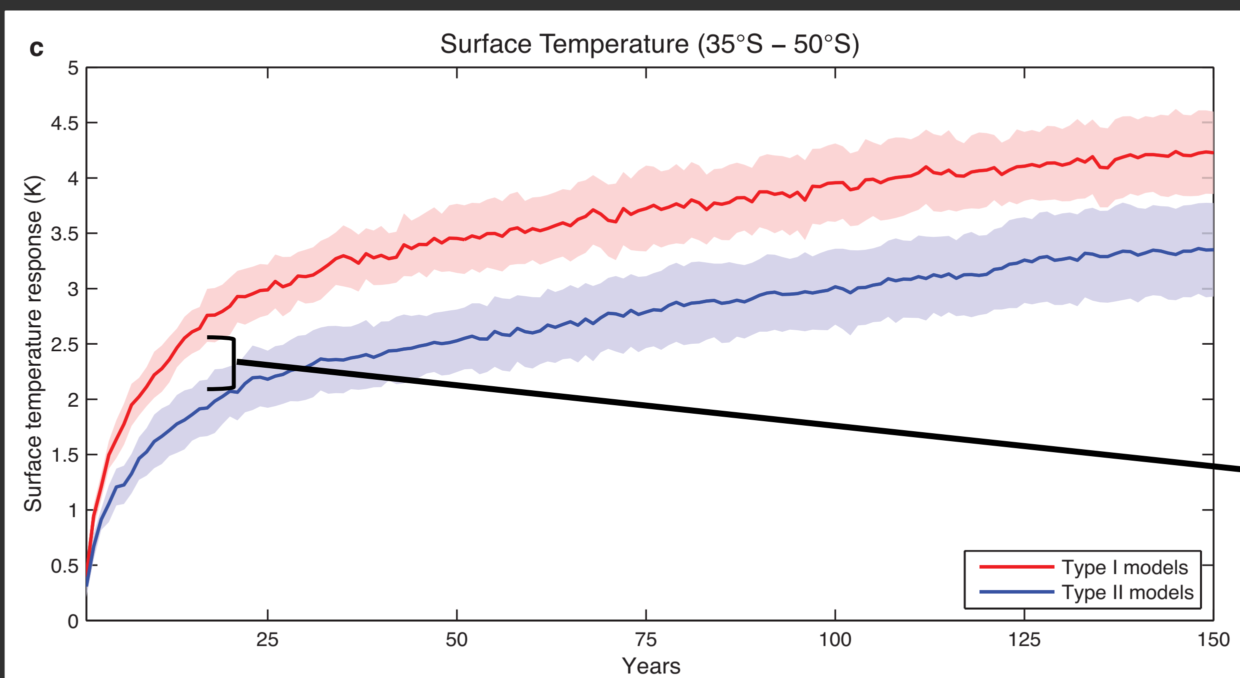
Implications for Climate Change

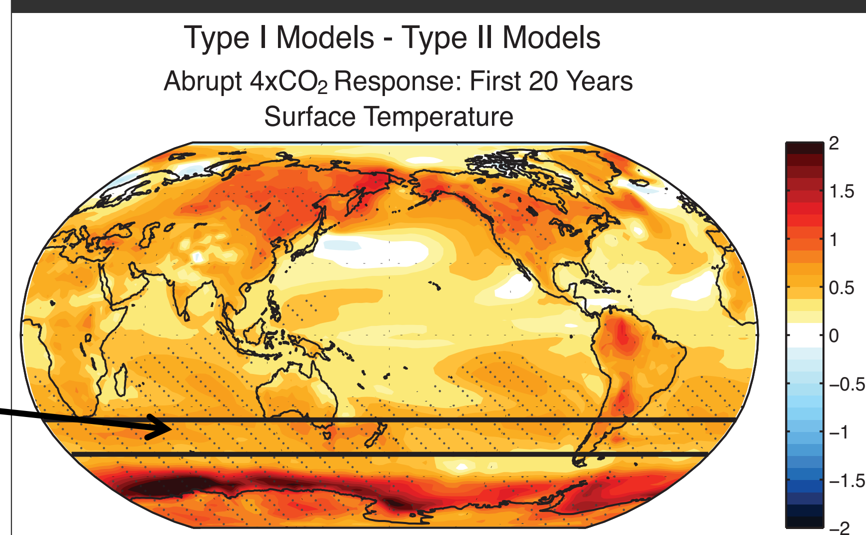
Idealized Experiment: Abrupt Quadrupling of CO_2

1) Jet shifts rapidly poleward in both classes of CMIP5 models.

2) Rapid reduction in reflection of shortwave radiation by clouds in Type I models only

3) Excess initial warming in SH in Type I models

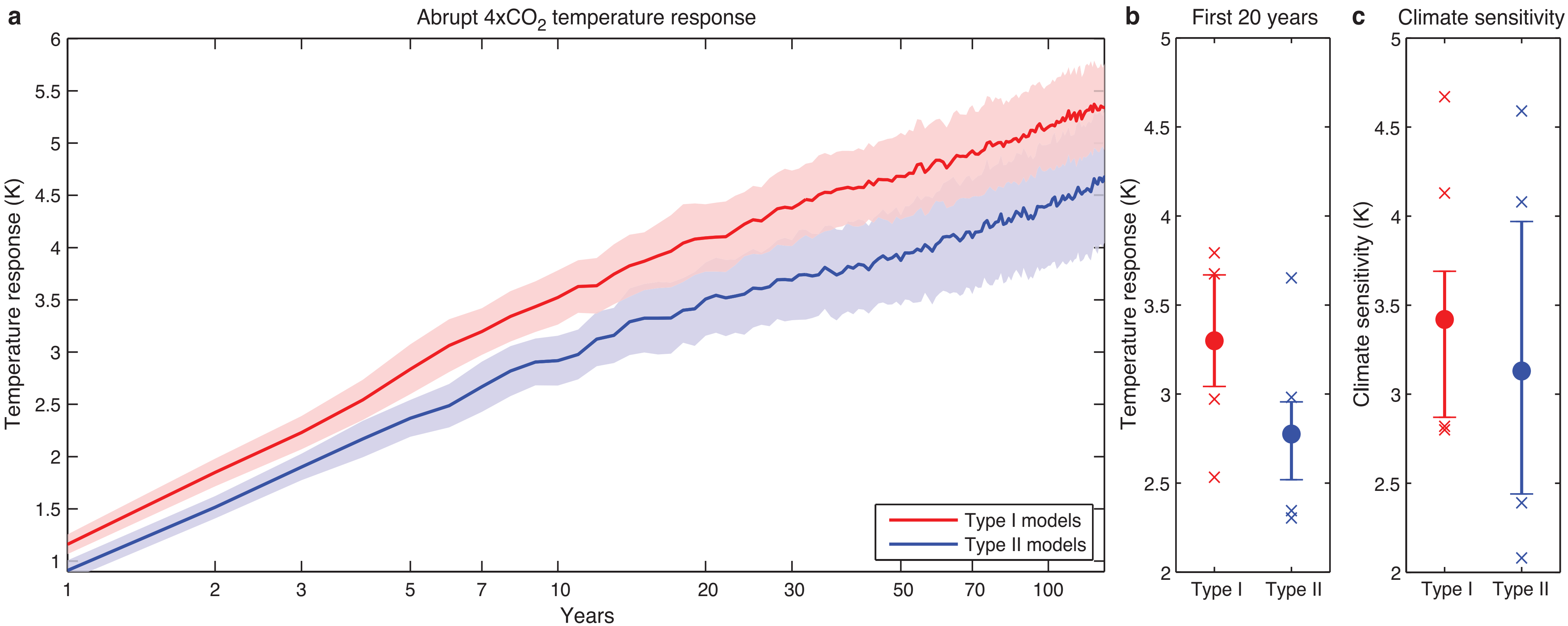




Grise and Polvani (2014, J. Climate)

Implications for Climate Change

Idealized Experiment: Abrupt Quadrupling of CO_2

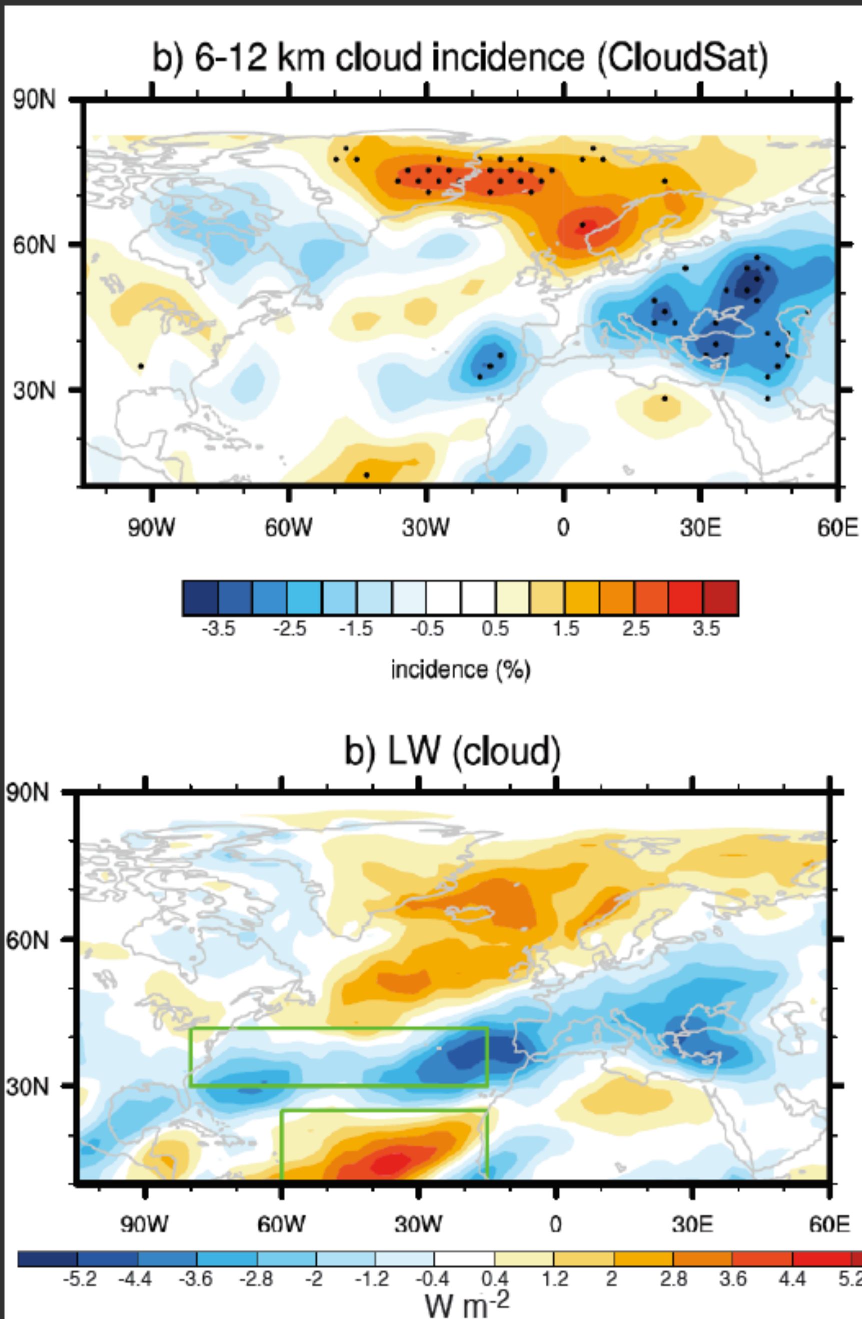


Grise and Polvani (2014, J. Climate)

Nearly instantaneous global warming response is significantly larger in the type I models.

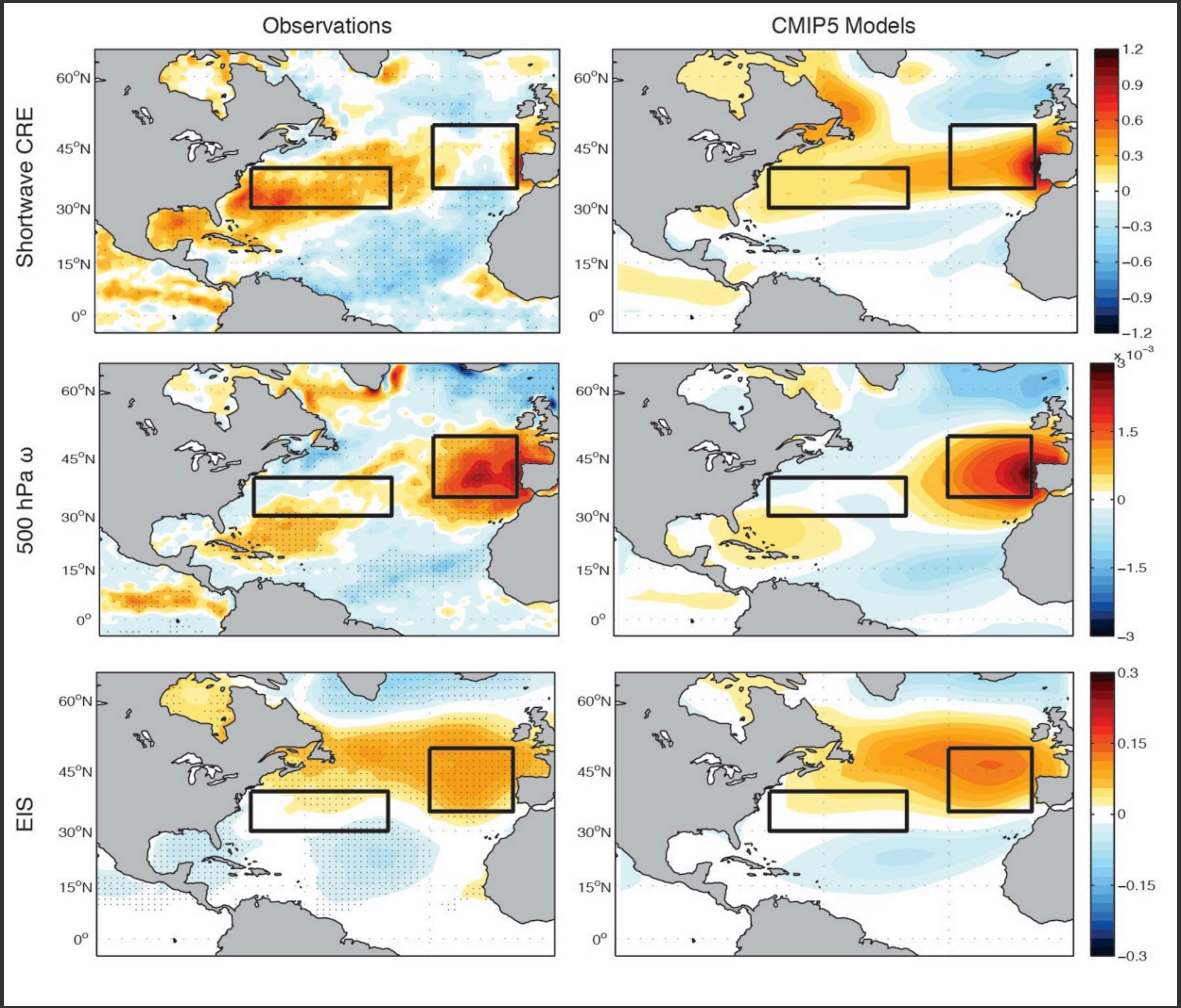
What about the Northern Hemisphere?

Li et al. (2014)

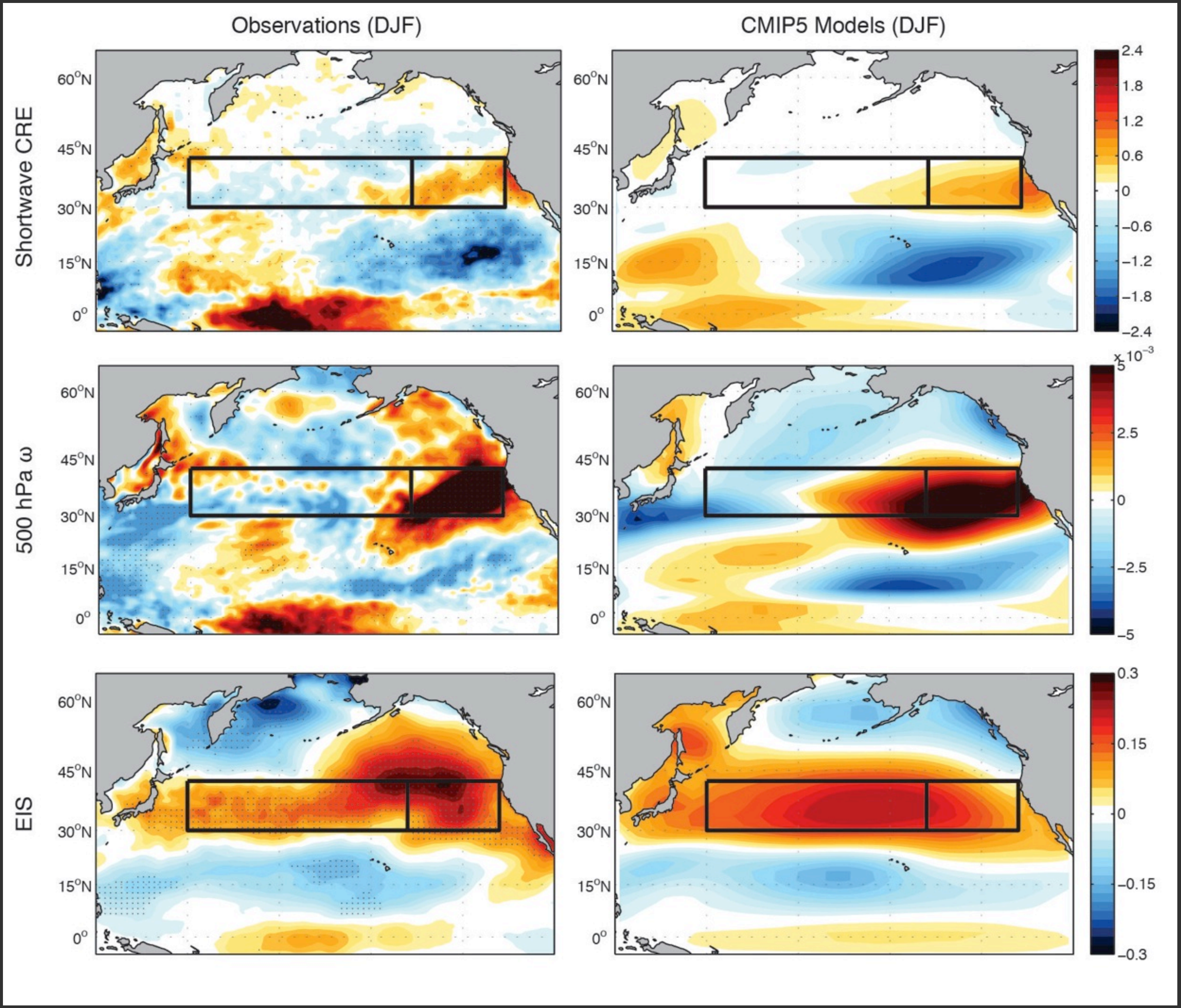


- Longwave cloud-radiative effect of Northern Annular Mode (NAM) is similar in structure to that found in SH.
- Shortwave cloud-radiative effect is weak during winter season.

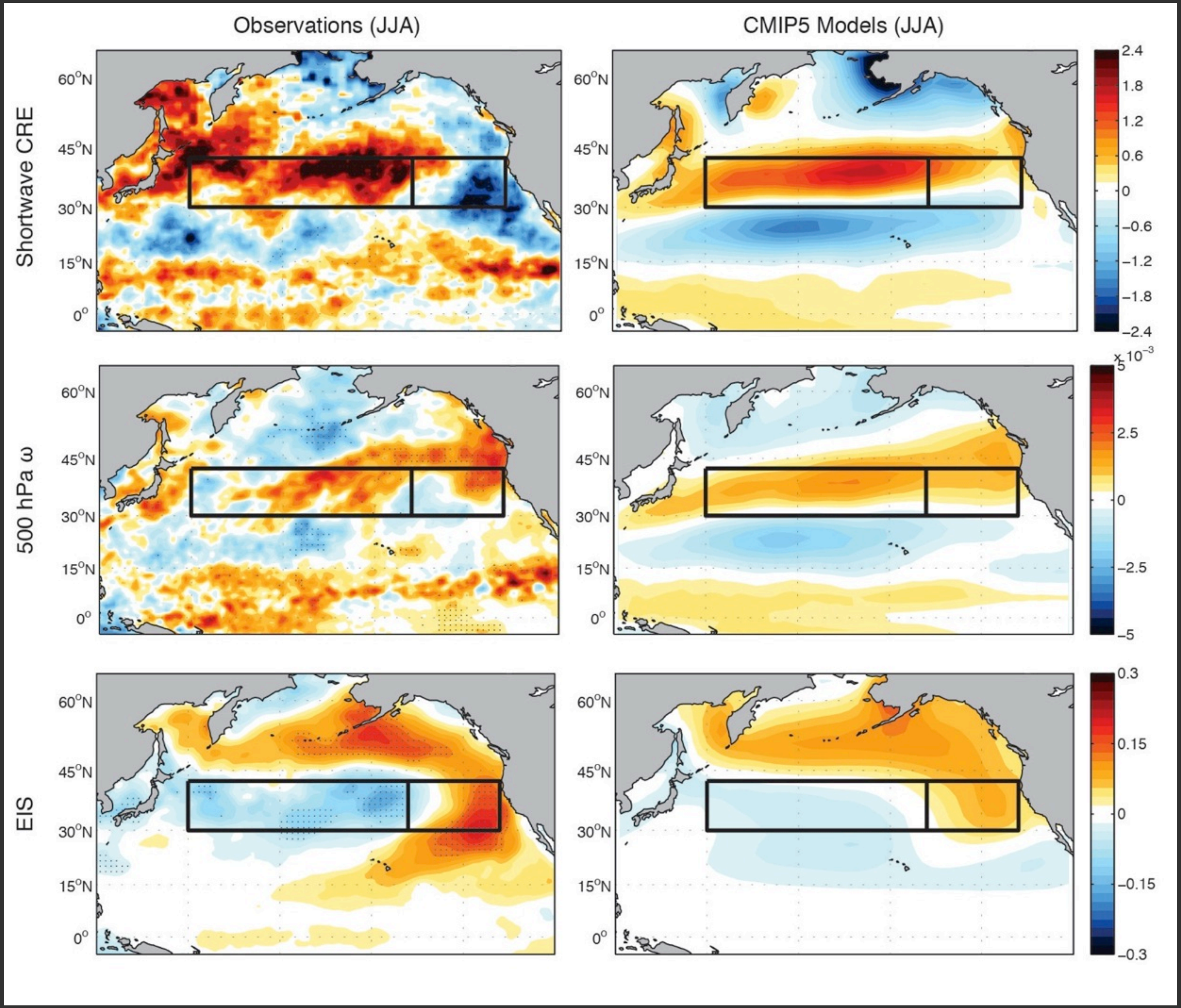
What about the Northern Hemisphere?



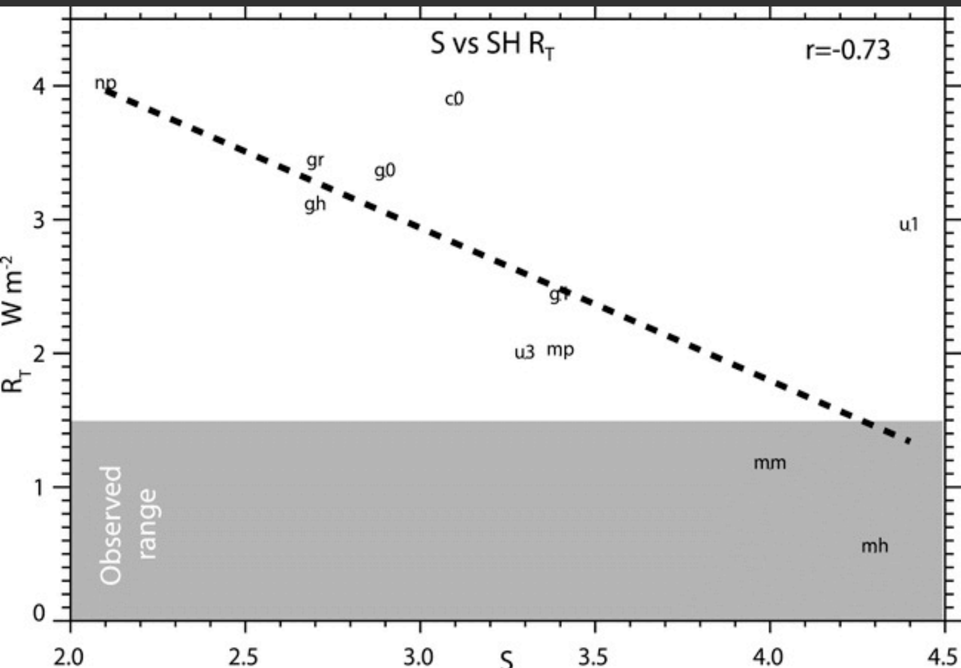
What about the Northern Hemisphere?



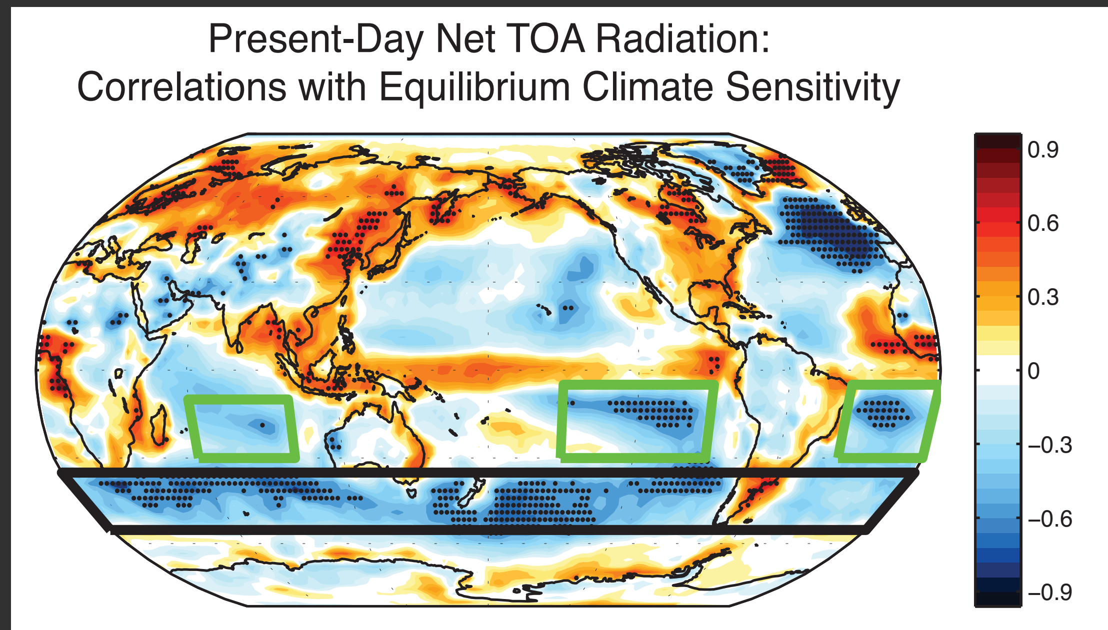
What about the Northern Hemisphere?



CMIP3 Models

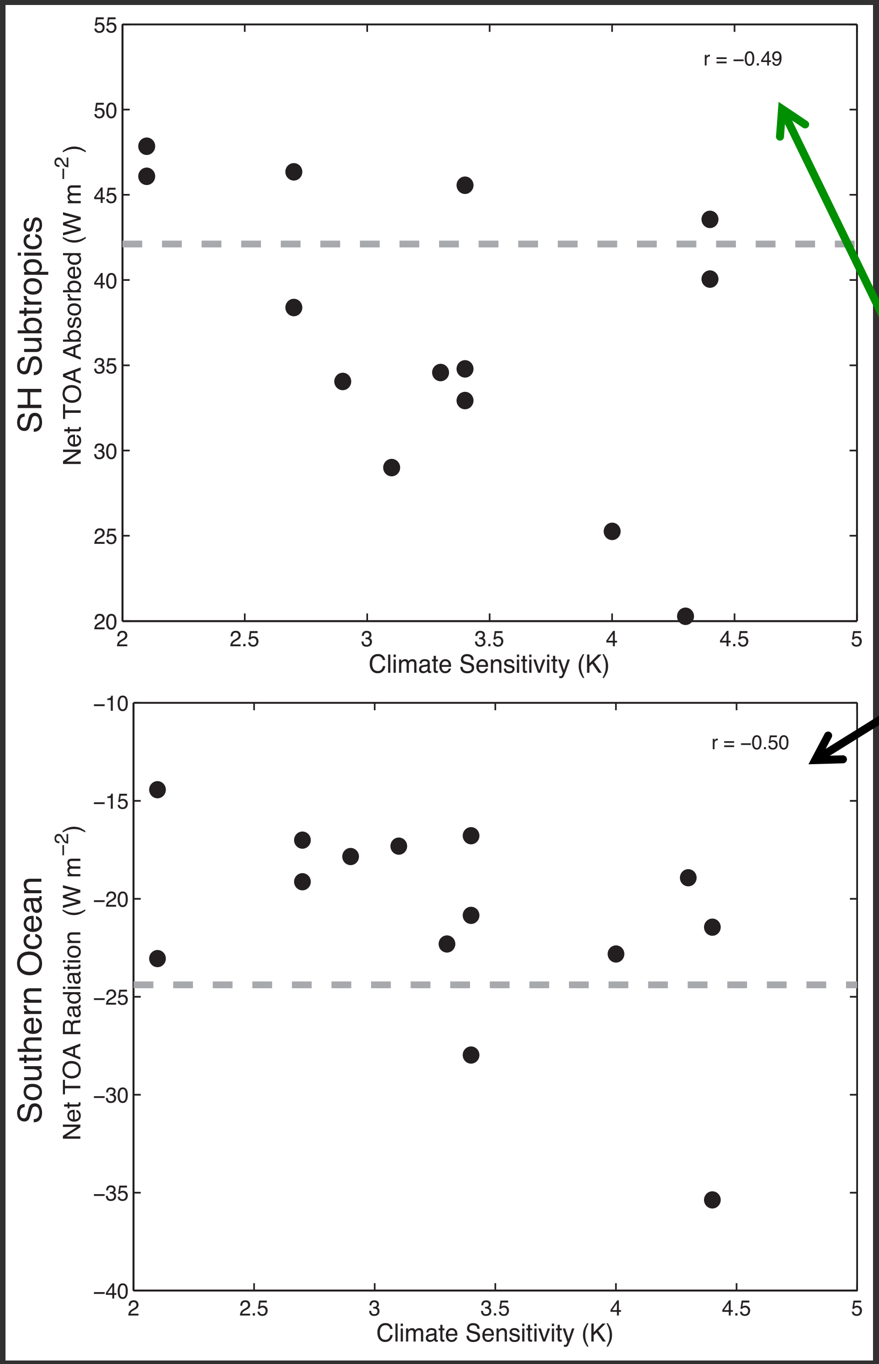


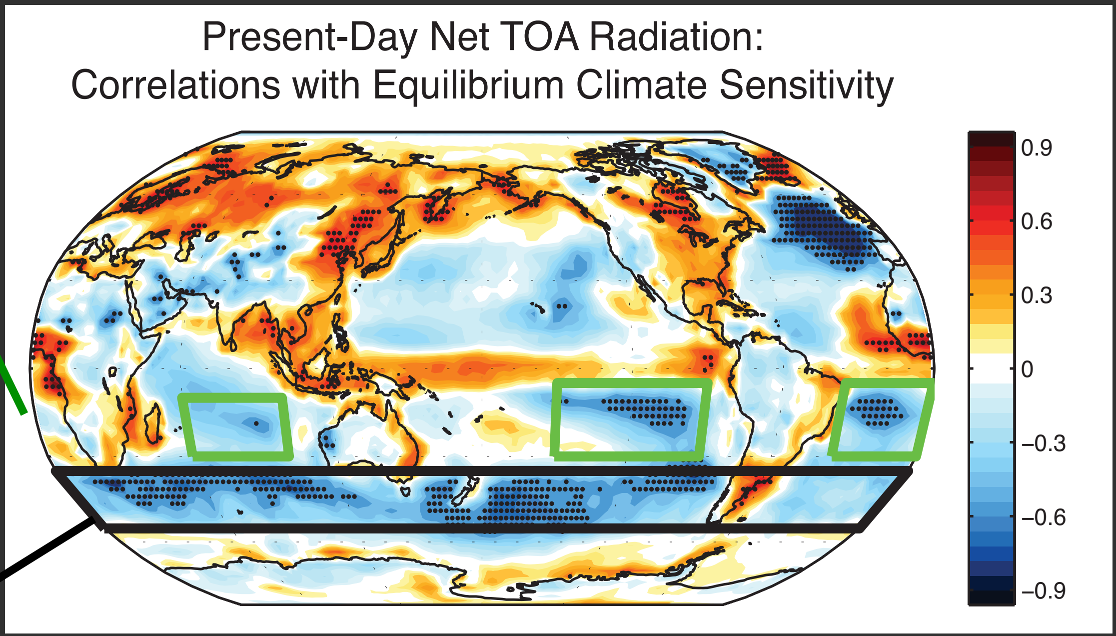
Trenberth and Fasullo (2010)



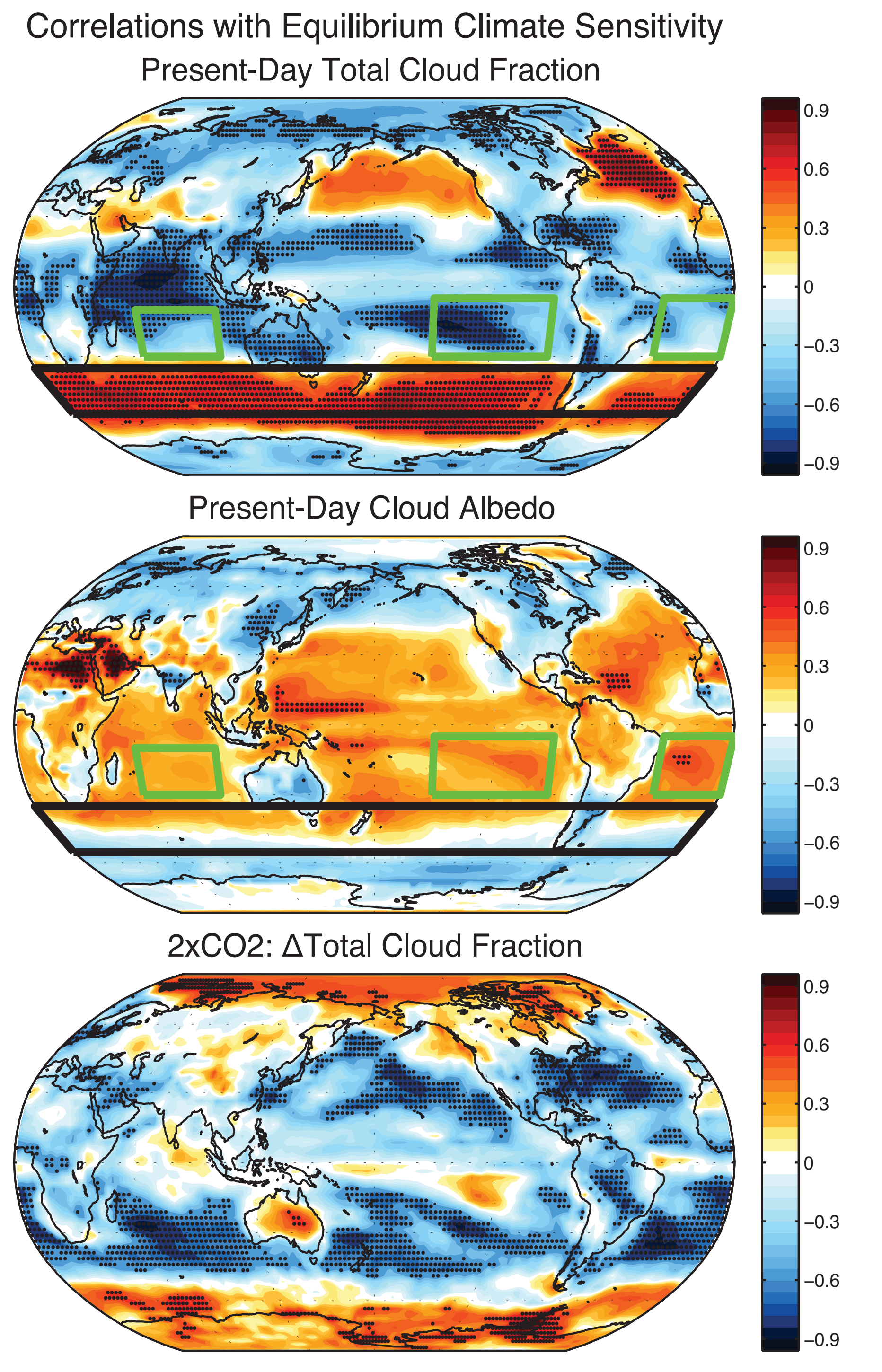
Relationship between climate sensitivity and present-day Southern Hemisphere radiation biases in CMIP3 models is **not** just about mid-latitudes!

CMIP3 Models





Understanding the CMIP3 Correlations

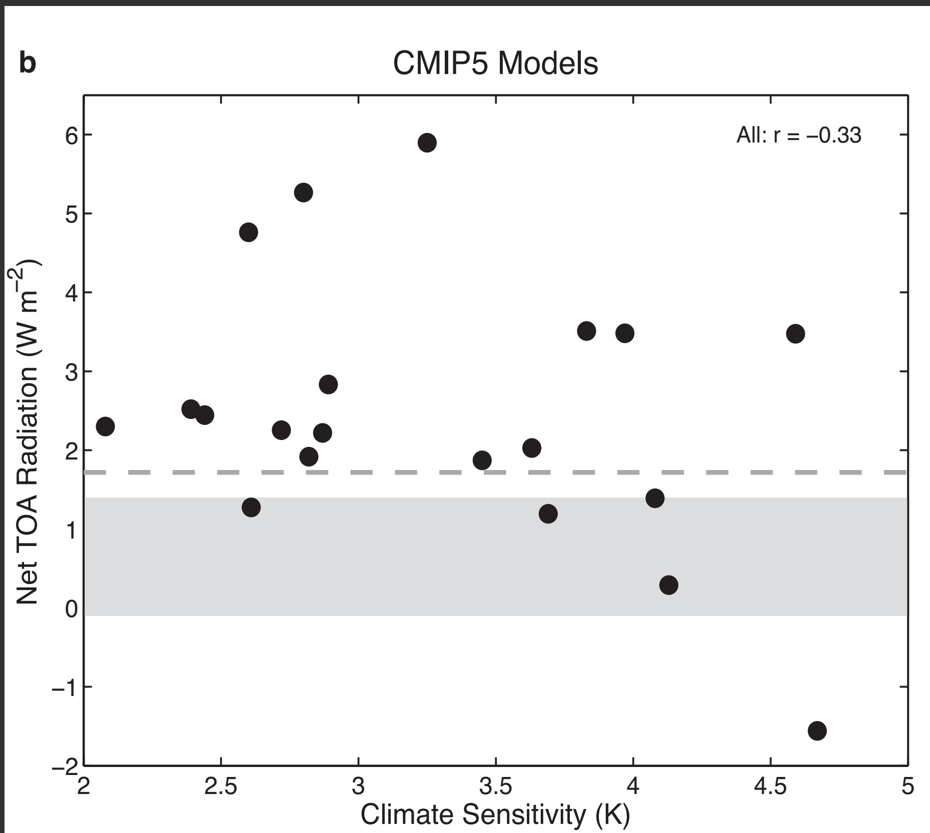


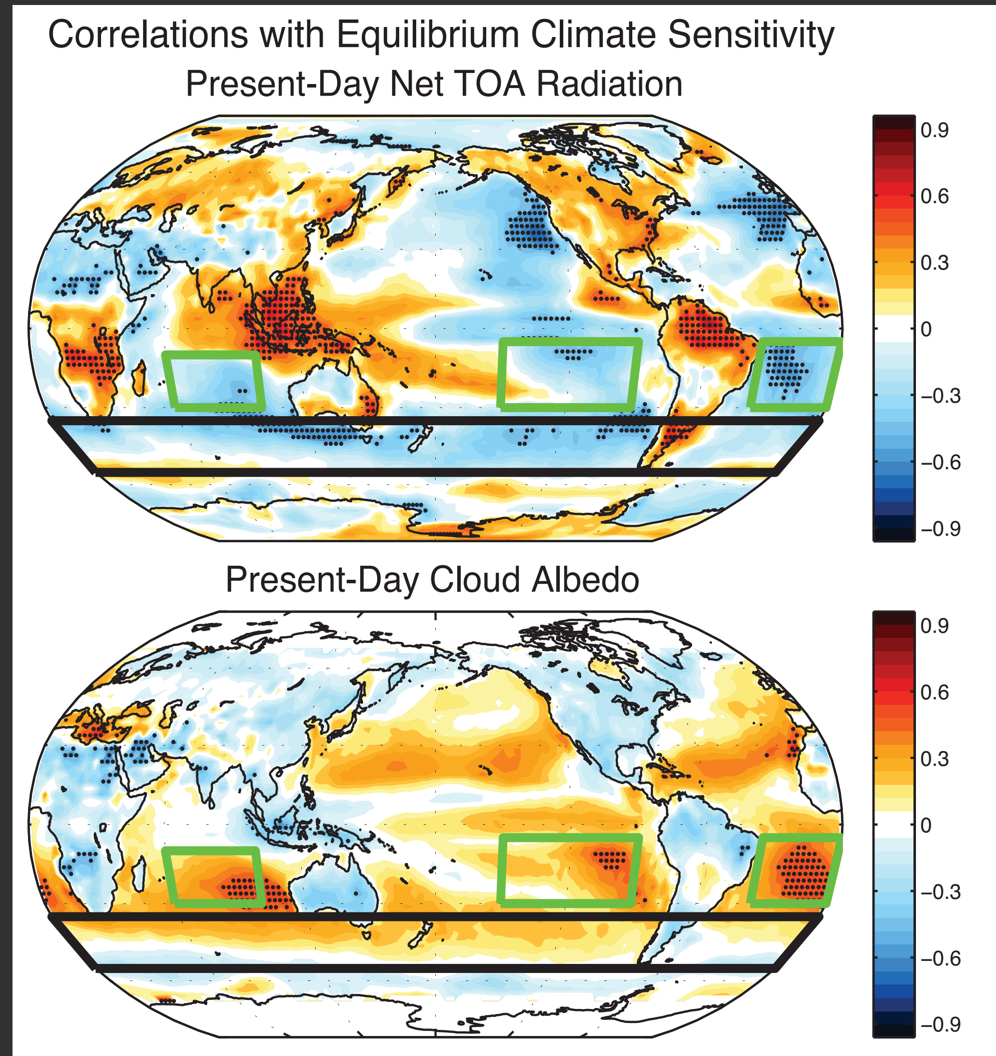
<u>Southern Ocean</u>: More present-day clouds, higher climate sensitivity (Trenberth and Fasullo 2010)

<u>SH Subtropics:</u> Brighter present-day clouds, higher climate sensitivity

<u>Increased CO_2:</u> Greater dissipation of subtropical clouds, higher climate sensitivity (Soden and Vecchi 2011)

CMIP5 Models

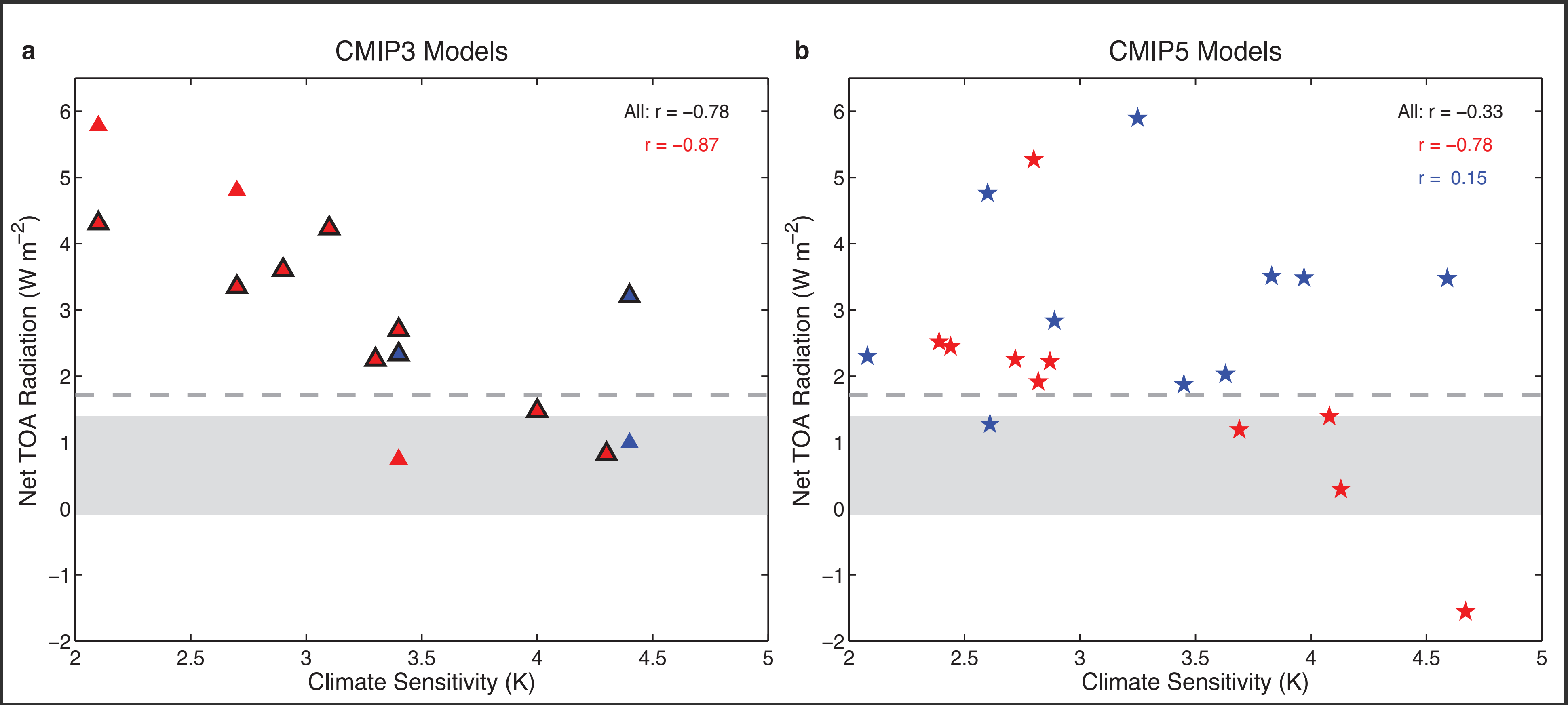




Subtropical correlations remain robust in CMIP5 models.

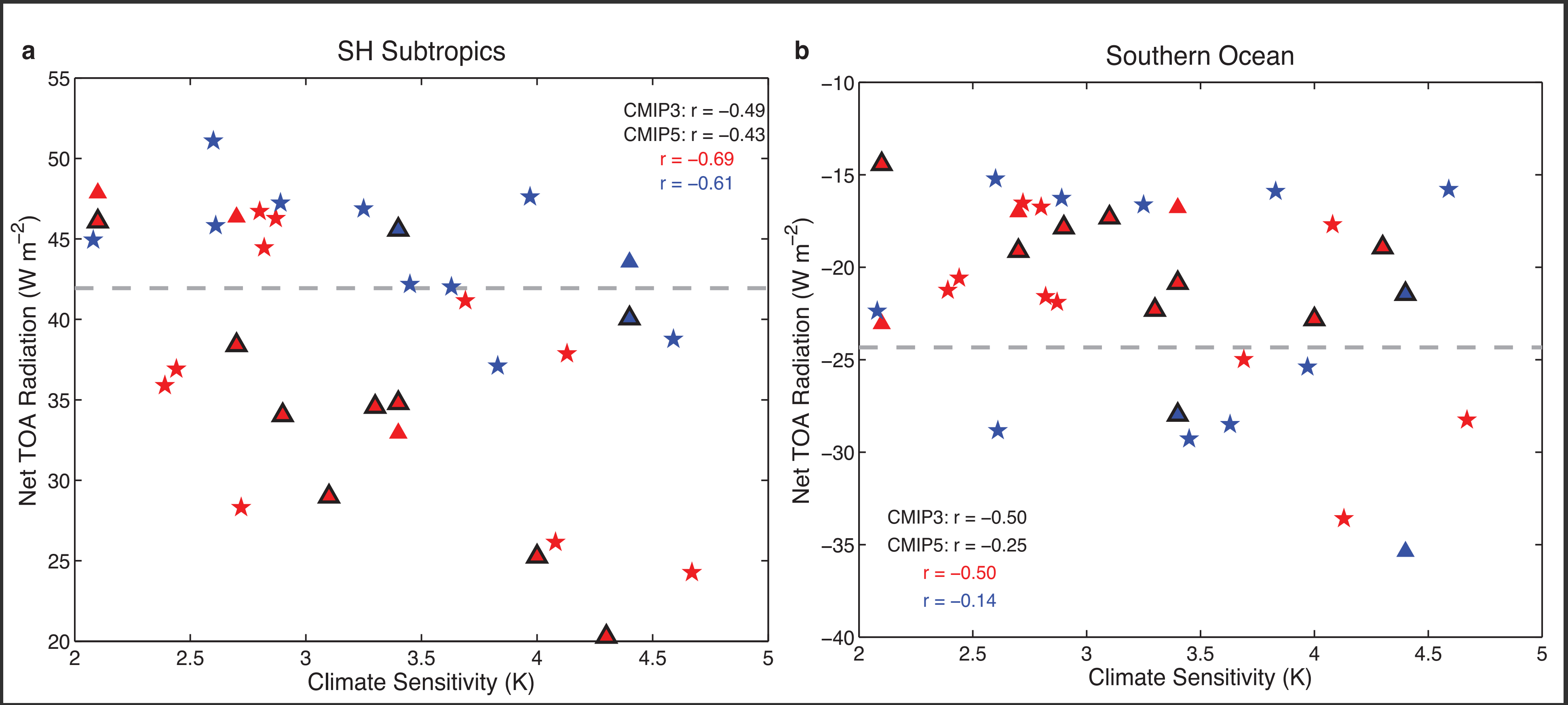
Southern Ocean (and thus hemispheric mean) correlations do not.

Subsetting CMIP Models by Subtropical Biases



Relationship between climate sensitivity and present-day SH net radiation biases is unique to models with large present-day biases in the **subtropics**.

Subsetting CMIP Models by Subtropical Biases



Subtropical correlations occur in both subsets of models.

Southern Ocean correlations only occur in models with large present-day biases in the **subtropics**.